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Petrology and Sedimentation of the Pennsylvanian Sediments in Southern Illinois: A Vertical Profile

Paul Edwin Potter
Herbert D. Glass

REPORT OF INVESTIGATIONS 204

ILLINOIS STATE GEOLOGICAL SURVEY
JOHN C. FRYE, *Chief*
URBANA, ILLINOIS

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PETROLOGY AND SEDIMENTATION OF THE PENNSYLVANIAN SEDIMENTS IN SOUTHERN ILLINOIS: A VERTICAL PROFILE

Paul Edwin Potter and Herbert D. Glass

ABSTRACT

An integrated study of outcrop and subsurface stratigraphy, sedimentary structures, petrography, and clay minerals was made of the Pennsylvanian sediments along a portion of the Eastern Interior coal basin border in southern Illinois. The data obtained were used to reconstruct Pennsylvanian provenance and depositional environments. Data relating to provenance were obtained primarily from the petrology and directional sedimentary structures of the sandstones. Studies of local and regional patterns of lithologic variation, kinds of sedimentary structures, and fossil content were the basis for environmental reconstruction.

This information indicates that the Pennsylvanian sediments in southern Illinois accumulated on a coupled coastal plain and shallow marginal marine shelf, both sloping to the southwest. Both coastal plain and shelf became progressively more negative and probably more gently dipping during Pennsylvanian time. Cross-bedding indicates that throughout the history of this coastal-plain—marginal-shelf, sediments were transported toward the southwest. Initially, the sediments in transport to and across this physiographic couple were derived from pre-existing sediments, but, as erosion progressively unroofed metamorphic and/or igneous rocks, immature clastics reached the basin.

Although the rate of basin subsidence was the controlling factor for contrasts in lithologic proportions and clay content of sandstones, it had only a negligible effect on clay mineral composition and produced no major change in sand transport mechanism.

INTRODUCTION

The primary objective of this study was to provide a closely integrated reconstruction of Pennsylvanian sedimentation in a small portion of the Eastern Interior coal basin. The second objective, of more general interest, was to determine what inter-relationships exist between stratigraphy (gross lithology), sedimentary structures, sedimentary petrology, and clay mineralogy in the coal measures of an intracratonic basin.

To achieve these objectives, a detailed field and laboratory study was made of some 1800 feet of the Pennsylvanian system exposed in and near Williamson County in southern Illinois. Emphasis was placed upon vertical variation over a limited area because 1) this minimized the area of field work, thus permitting more detailed observation, 2) it favored the laboratory study of a greater rather than a smaller number of variables, and 3) it maximized the likelihood of contrasts between depositional environments and minimized the effect of regional variations. An abundance of subsurface diamond-drill hole samples and logs supplemented outcrop study. Because the area is very small in relation to the distributive processes of Pennsylvanian sedimentation in either the north-central United States or even in the Eastern Interior coal basin, this study may be considered an essentially vertical "point" profile.

In presenting the results we have tried to separate geologic description, be it stratigraphic or petrologic, from geological interpretation. Thus, the sections on "Regional Setting," "Stratigraphy," "Sedimentary Structures," and "Petrology" are descriptive, as opposed to the interpretative sections on "Provenance," "Environment," and "Tectonics and Climate."

A companion publication, "Geology and Coal Resources of the Pennsylvanian System in Williamson and Adjacent Parts of Johnson and Union Counties, Illinois" (in preparation), covers much the same area as this report and was part of the same research project. Its primary objective is an evaluation of the area's coal resources.

In contrast, the present study is a contribution to fundamental sedimentary rock research. As such it represents the belief of the Illinois State Geological Survey that research directed toward fundamental objectives is basic to future practical research.

Acknowledgments

The technical and geological assistance of other Survey members did much to make our study more comprehensive. Gordon Smale and Russell Lennon helped collect and process some of the samples. Dale Farris made the photographs of outcrops and cores. The geological criticisms by W. F. Bradley, R. M. Kosanke, W. H. Smith, J. A. Simon, and H. B. Willman, all of the Illinois State Geological Survey, were most helpful.

The photographs of modern Gulf Coast sediment cores were supplied by Hugh Bernard, Shell Development Corp., Houston, Texas. L. M. J. U. Van Straaten, Geological Institute, Rijks University, Groningen, Netherlands, supplied the pictures of the modern Wadden Sea sediments. E. C. Dapples, Northwestern University, Evanston, Illinois, F. J. Pettijohn, Johns Hopkins University, Baltimore, Maryland, Raymond Siever, Harvard University, Cambridge, Massachusetts, and Tj. H. Van Andel, Scripps Institution of Oceanography, LaJolla, California, read the manuscript and made helpful suggestions.

Regional Geology

paleozoic setting

The major tectonic elements of the northeastern United States in relation to the area of study are shown in figure 1. These include the crystalline-metasediment core of the Appalachians, the Canadian shield, and four major Paleozoic basins—the Appalachian, Michigan, Eastern Interior, and Mid-Continent coal basins—that have been isolated from one another by post-Paleozoic tectonics and erosion. Of the four basins, the Michigan and Eastern Interior basins and large portions of the Mid-Continent basin lie on the buried south-central flanks of the Canadian shield.

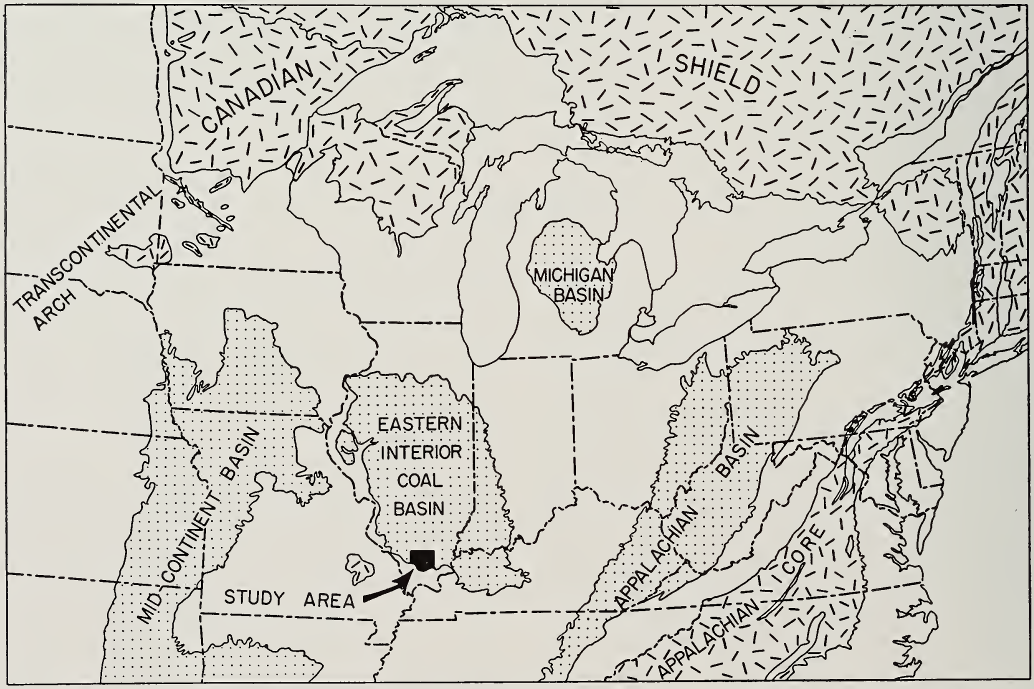

Fig. 1. — Regional setting showing relation of study area and some major Pennsylvanian basins.

Throughout most of Paleozoic time, the buried flanks of the shield served, in the north-central states, as a slowly subsiding platform for the accumulation of the typical products of cratonic sedimentation — dominant and widespread carbonates, and clastics consisting essentially of shales and orthoquartzitic sandstones.

Beginning in Chester (Upper Mississippian) time, sandstones became more abundant but continued to be orthoquartzitic in character (Siever, 1953). In the Eastern Interior coal basin, a major unconformity separates the Mississippian from the Pennsylvanian (Weller and Bell, 1937, p. 777; Weller and Sutton, 1940, p. 847-850; Siever, 1951). Paleozoic sedimentation terminated in the Illinois area with the overwhelming dominantly clastic Pennsylvanian sedimentation that began with the deposition of orthoquartzitic sandstones and ended with the deposition of subgraywacke sandstones.

EASTERN INTERIOR COAL BASIN

The Eastern Interior coal basin covers an area of approximately 53,000 square miles (Wanless, 1955, p. 1753) in portions of Illinois, Indiana, and Kentucky. The Pennsylvanian rocks rest unconformably on sediments that range from upper Chester (Kinkaid) along the basin's southern border to Ordovician along its northern border. Significant erosion occurred during the Mississippian-Pennsylvanian interval, which closed with epeirogenic uplift that produced an integrated system of south - southwestward oriented channels (Siever, 1951; Wanless, 1955, p. 1764-1766). The channels have typical dendritic patterns and are entrenched as much as 200 feet. In Williamson County, subsurface data are insufficient for detailed mapping of the channels but indicate as much as 100 feet of relief on the Kinkaid limestone.

The regional structural elements of the basin include a series of anticlines and monoclines and two prominent post-Pennsylvanian fault systems, the Wabash Valley and the Cottage Grove - Rough Creek (fig. 2-A). The Eastern Interior coal basin can be further divided into a structurally deep portion and a surrounding shallower basin margin (fig. 2-A). The elevation of coal No. 2 above sea level (fig. 2-A) rather generally defines the structural contrast. Figure 2-B shows the areas of differential subsidence in the basin and indicates that the rapidly subsiding portion of the basin continued an undetermined distance south of the present southern outcrop limit (Wanless, 1955, p. 1780). To the west and north the rapidly subsiding portion was separated from a shelf area by a transition zone.

With the exception of the basal Caseyville and Mansfield sediments, largely restricted to the rapidly subsiding portion of the basin and the eastern transition zone, differences between shelf and basin sedimentation are best expressed in contrasting interval thicknesses rather than in major contrasting facies of sedimentation. Thicknesses of more than 2000 feet are typical for the rapidly subsiding portion of the basin. The area of study in and near Williamson County lies in the rapidly subsiding portion of the basin.

STRATIGRAPHY AND LITHOLOGY

The 1800 feet of Pennsylvanian sediments in and near Williamson County range in age from Lower Pennsylvanian (Caseyville group) through Middle Pennsylvanian (Tradewater, Carbondale, and the lower portion of the McLeansboro group) to Upper Pennsylvanian (upper portion of the McLeansboro).* The stratigraphic column (fig. 3) shows the boundaries of these groups, their relation to the Morrowan, Atokan, DesMoinesian, and Missourian series (Siever, 1956), and the more prominent lithologic units in each group. Figure 4 shows the areal extent of the stratigraphically younger rocks not present in the area studied.

Average thicknesses of the four stratigraphic groups in and near Williamson County are shown in figure 3. Thinning

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* See Wanless (1956) and Siever (1956) for a complete discussion of this classification.

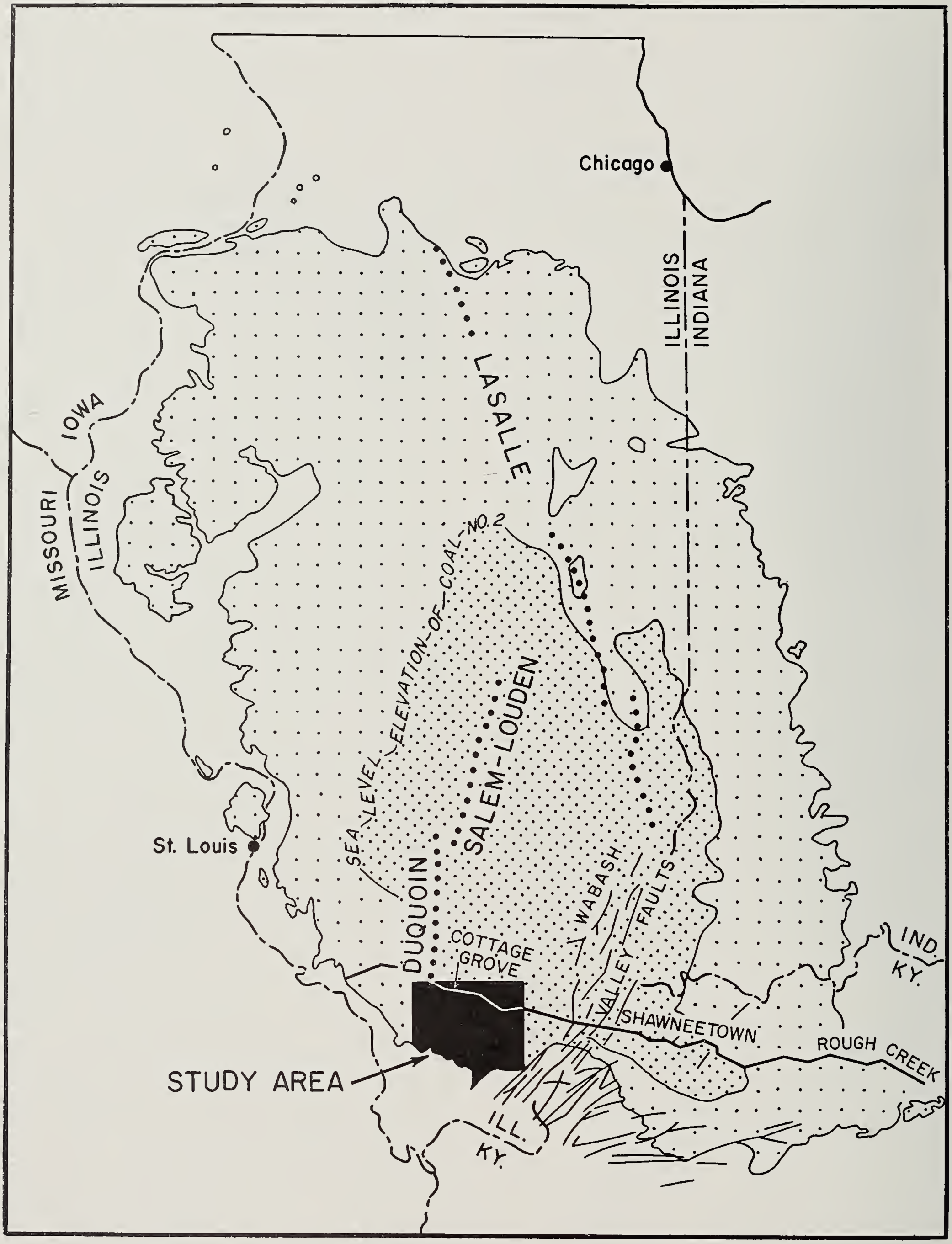


Fig. 2A. — Generalized structure of Pennsylvanian sediments in the Eastern Interior coal basin showing the structurally deep part of the basin and some prominent anticlines and faults (modified and adapted from Wanless, 1955).

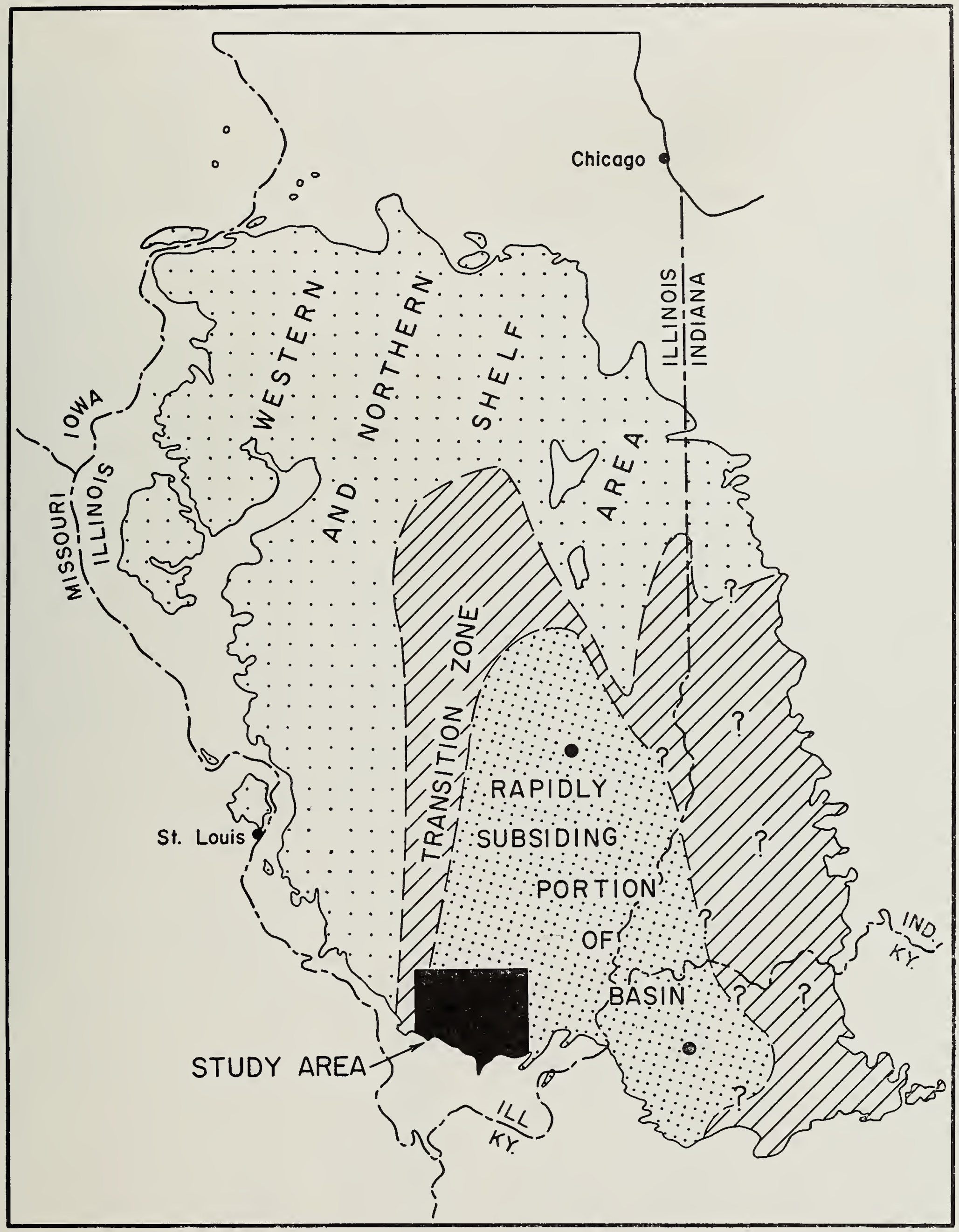


Fig. 2B. — Areas of differential subsidence in the Eastern Interior coal basin. Large black circles show location of two areas of present maximum thickness.

from north to south appears to be negligible, but there is more thinning from east to west across the area.

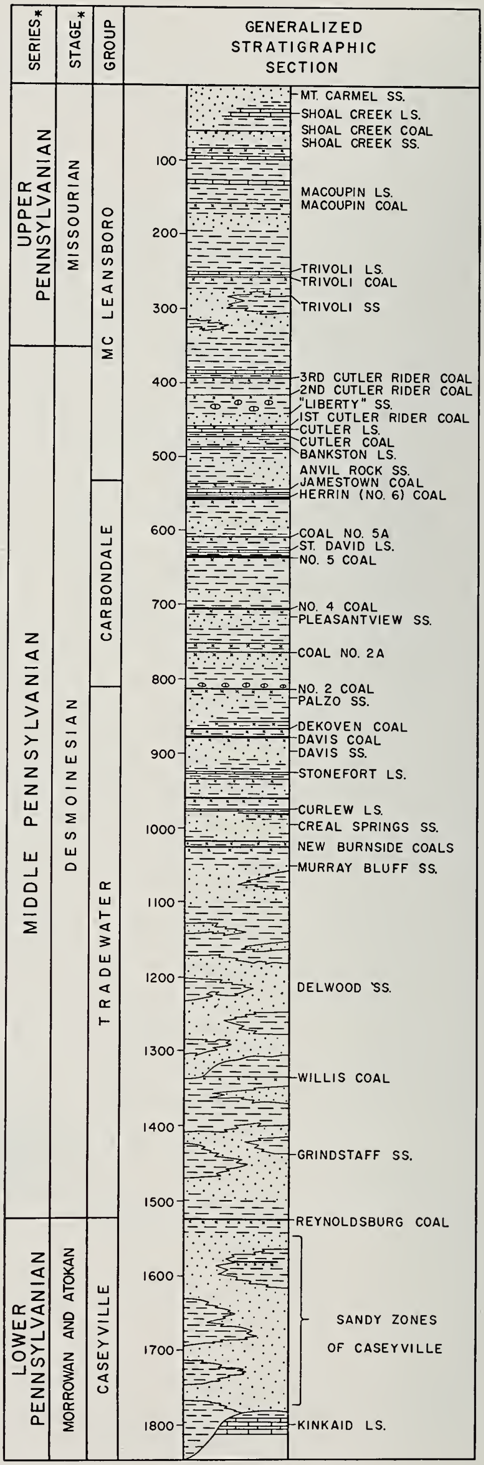
The megascopic rock properties exhibit significant vertical variation (table 1). In general the sediments below New Burnside coals have properties different from those above the New Burnside coals.

Below the New Burnside coals, shales are approximately equal volumetrically to sandstones, there are no known limestones, and coal beds generally are less than 2 feet thick and not laterally persistent. Marine invertebrate fossils are present but very rare. In this zone of dominantly clastic rocks, it is difficult to trace with certainty many of the sandstones.

Below the New Burnside coals, however, the top of the Caseyville marks a sharp break in sandstone type. The sandstones of the Caseyville are clean quartz sands that commonly contain well rounded quartz pebbles. Beginning with the overlying Grindstaff sandstone (fig. 3), the Tradewater sandstones become micaceous and argillaceous. Coal, shale, and concretionary fragments replace the quartz pebbles as the prominent conglomeratic elements. The lower Tradewater sandstones are transitional between those of the Caseyville and those above the New Burnside coals. The lithologic contrast between the sediments above and below the New Burnside coals is shown in figure 5.

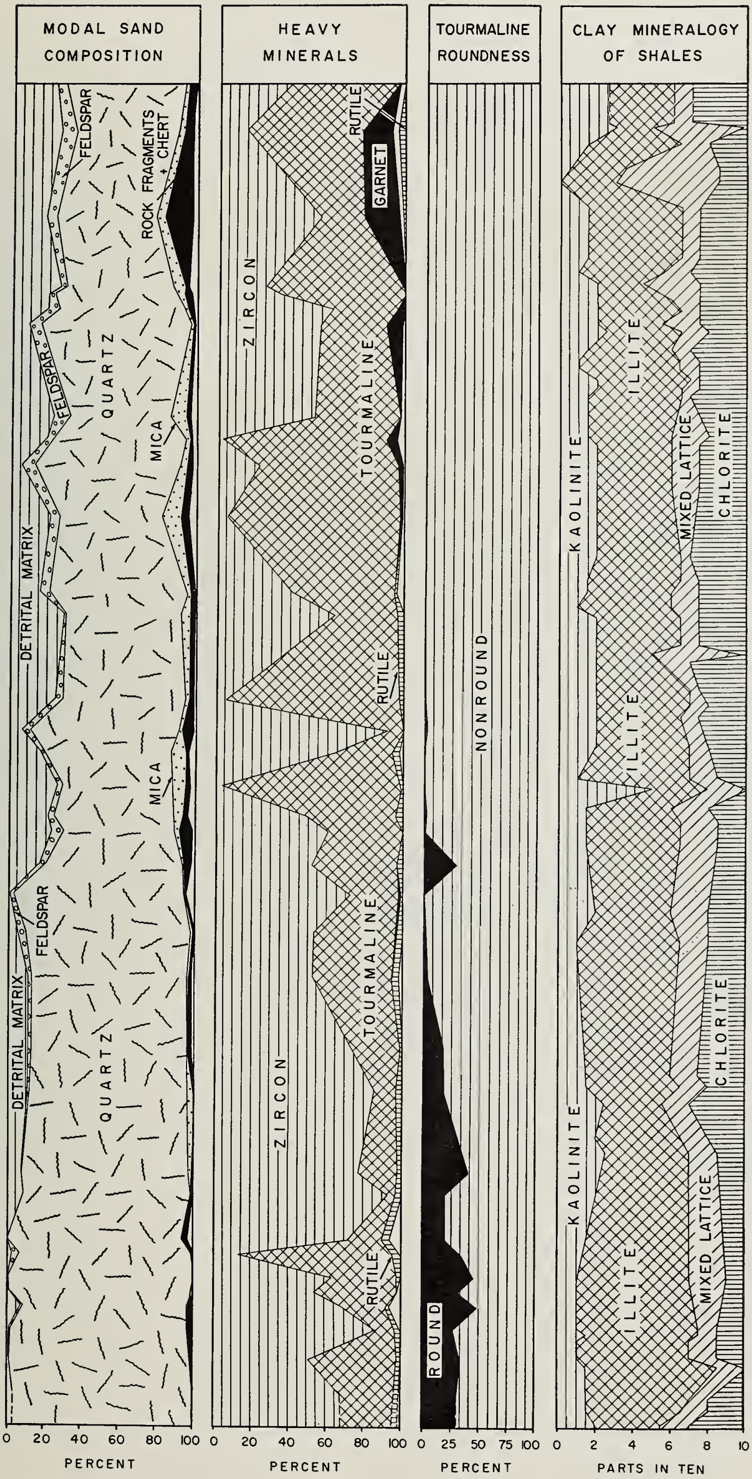
Above the New Burnside coals there is much less sandstone and much more shale (marine fossils common) than below. Abundantly fossiliferous limestones and black fissile shales become significant. Compared to their frequency in the older underlying sediments, coal beds are abundant. The limestones, black fissile shales, coal beds, and underclays commonly can be traced over many counties.

The sandstones above the New Burnside coals are uniformly argillaceous and micaceous. Typically, they are the "salt and pepper" textured subgraywackes.



*Series and stage taken from Moore and Thompson (1949)

FIG. 3. — Generalized stratigraphic



column and vertical mineralogic variation.

TABLE 1.—VERTICAL CONTRASTS IN PENNSYLVANIAN SEDIMENTATION IN THE WILLIAMSON COUNTY AREA

Stratigraphic groups	Intervals	Dominant lithology	Coal beds	Limestones	Cyclical sedimentation	Fossil content		Megascopic characteristics of sands	
						Marine invertebrates	Plants	Sandstone type	Conglomerates
McLeansboro	Mt. Carmel sandstone to Coal No. 6	Shales greater than sandstones and both much greater than limestones	Fair development and widespread	Optimum development and widespread	Well developed	Common in limestones and in some shales; present in some sandstones	Carbonized and pyritized plant remains and compressions commonly present in shales and sandstones	Dirty "salt and pepper" micaceous sandstone	Locally derived pebbles and cobbles of coal, concretionary fragments, shale and limestone
Carbondale Tradewater	Top of coal No. 6 to New Burnside coals		Optimum development and widespread	Fair development					
Caseyville	New Burnside coals to base of Pennsylvanian system	Shales approximately equal to sandstones	Very poor development and not widespread	No known limestones	Poorly developed	Present but very rare		Transition zone Clean quartz sandstone	Dominantly well rounded far traveled quartz pebbles

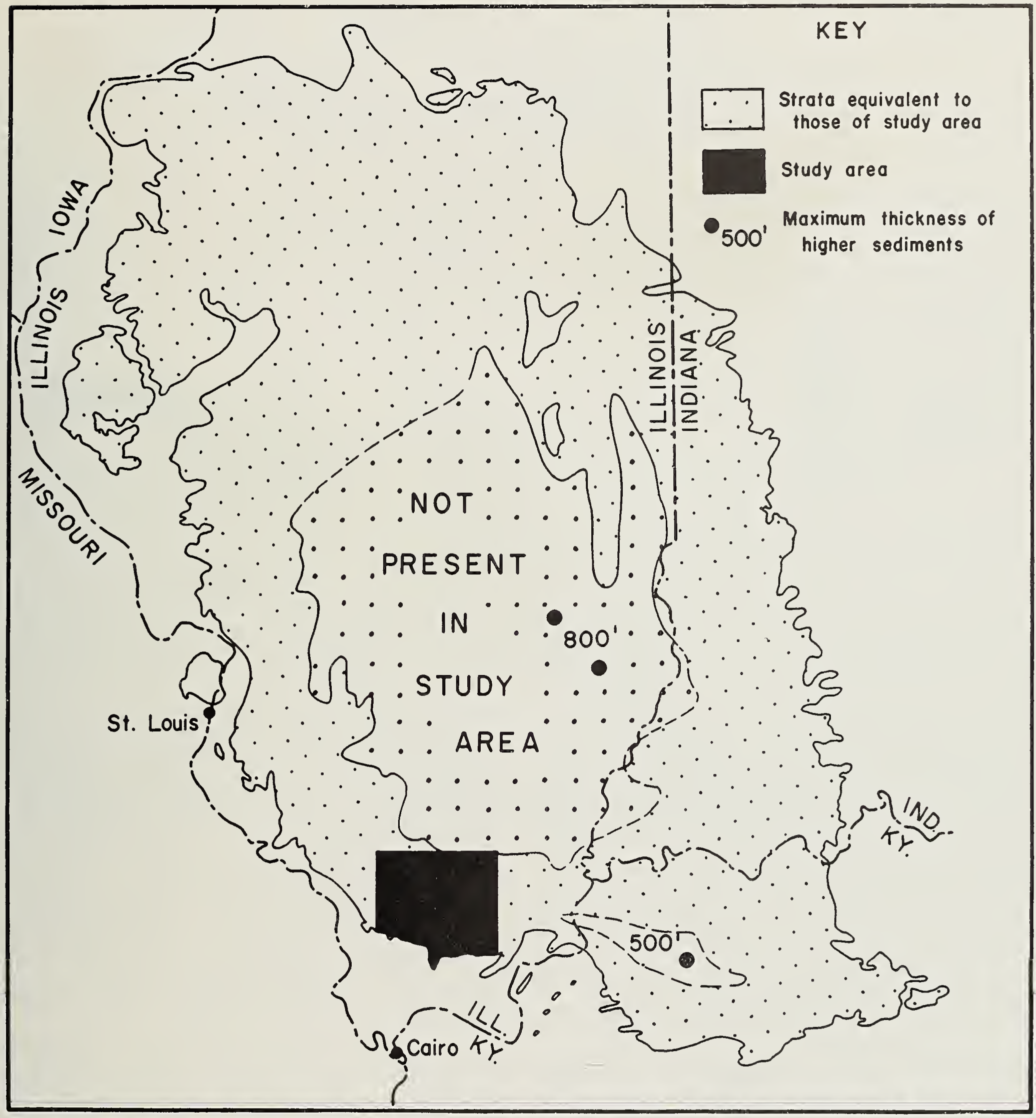


Fig. 4. — Areal extent (open stipple) of younger Pennsylvanian sediments not present in study area (modified and adapted after Wanless, 1955, p. 1778-1779, fig. 7).

The clean quartz sandstones of the Caseyville group and the micaceous-argillaceous sandstones above the New Burnside coals are in hand specimen quite distinct from each other (pl. 6). Within either facies, however, individual sandstones generally cannot be distinguished in hand specimen. The conglomeratic elements of the subgraywacke sandstones consist of such locally derived materials as fragments of reworked concretions, coal, limestone, and shale. Well rounded quartz pebbles like those of the Caseyville never have been observed.

In contrast to the above vertical variations, the abundance of tree-trunk casts in the sandstones and leaf compressions in the shales is much the same throughout the section. Nor is there a major change in the color of the interbedded shales.

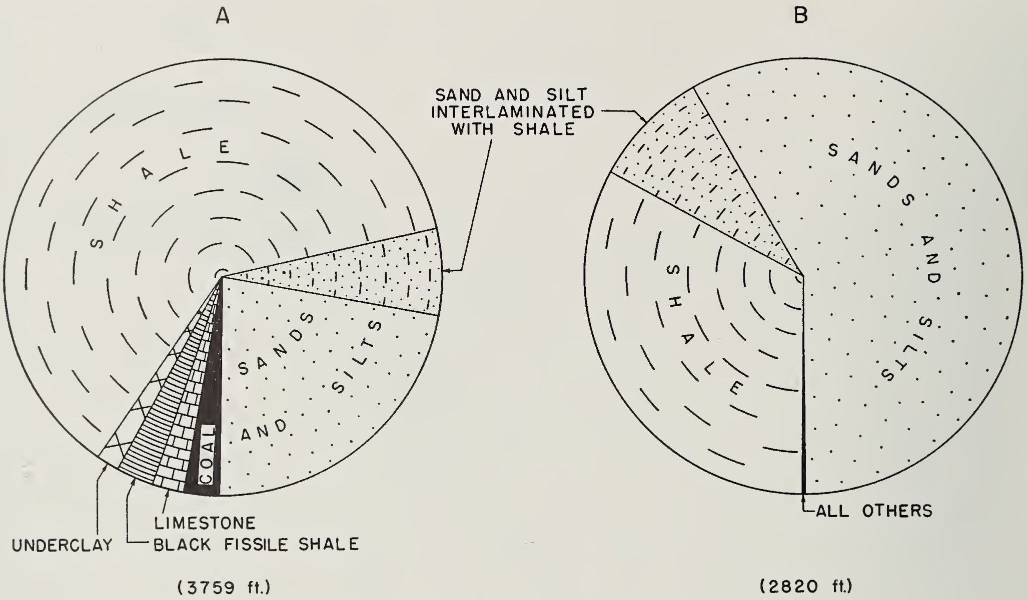


Fig. 5. — Contrasting lithologic proportions above the New Burnside coals (A) and below the New Burnside coals (B). Numbers in parentheses represent the total footage of diamond drill core upon which estimate is based.

Although greenish gray shales are more common above the New Burnside coals, dominant shale colors throughout the section are medium to dark gray. Hence the striking contrast between hand specimens of the basal clean quartz sandstones and upper subgraywacke sandstones does not extend to their associated shales.

Two significant megascopic features of sediments deserve special comment — sand-body shape and small-scale vertical lithologic variation. Because of the presence of interbedded marker beds (coals and limestones), sand-body shape is most readily ascertained in the sediments above the New Burnside coals. The development of sandstone channels is the most prominent morphologic feature of the sandstones. In nearby Jefferson County, Illinois, Mueller and Wanless (1957) made a study of this channel behavior (fig. 6). Qualitatively, the channel fill is coarser-grained, more cross-bedded, and more commonly conglomeratic than its non-channel equivalents. In non-channel areas, the sands are finer-grained and generally conformable with the underlying rocks. The presence of channel sandstones that have eroded stratigraphic marker beds and changed stratigraphic intervals through differential compaction locally complicates correlation. The absence of well defined and traceable marker beds below the New Burnside coals makes it difficult to obtain data on the shape of sand-bodies in the Lower Tradewater and Caseyville.

Small-scale vertical lithologic variation is restricted below the New Burnside coals because the sediments consist essentially of two components — shale and sand. There is little lithologic contrast above and below the thin coal beds of this sequence. The advent of more definitely marine sedimentation above the New Burnside coals produced pronounced vertical lithologic contrast above and below coal beds. Fossiliferous (marine invertebrates) shales, limestones, and black fissile shales are found above coals; underclays, nodular limestones, and generally nonfossiliferous shales and sandstones are below coals. Such a sequence of lithologic units, ideally consisting of 10

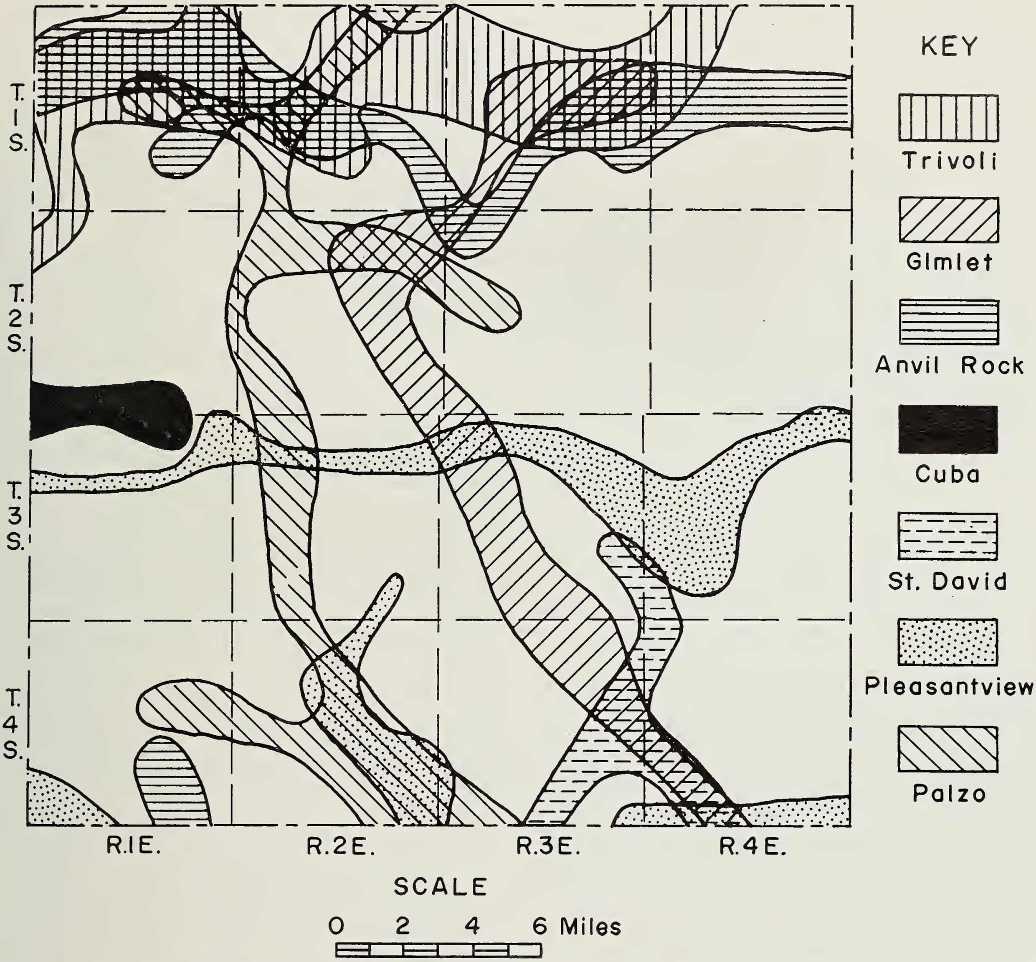


Fig. 6. — Channel behavior of Pennsylvanian argillaceous sandstones above the New Burnside coals in nearby Jefferson County, Illinois (from Mueller and Wanless, 1957).

units (several different types of limestones and shales are recognized) has been termed a cyclothem (Wanless and Weller, 1932). Ideally this ordered lithologic sequence can be represented, from its basal sand (A), through the coal (E), to the final shale (J), by the single permutation:

A B C D E F G H I J

wherein A = sandstone; B = gray sandy shale; C = "freshwater" limestone; D = underclay; E = coal; F = gray shale (some marine fossils); G = limestone (marine fossils); H = black shale (marine fossils); I = limestone (marine fossils); J = gray shale (marine fossils). Although any single section rarely contains all the units, the order is commonly (but not always) preserved so that the actual cyclothem may consist of only the units

A B D E G H J

or

A B D H G

or even only

D E J

The tendency for the development of ordered lithologic sequences, complete or incomplete, is the most prominent charac-

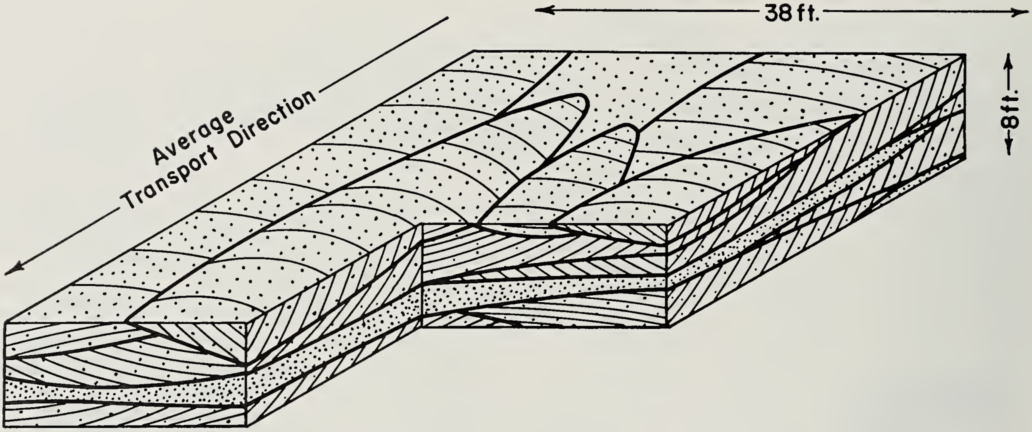


Fig. 7. — Block diagram of a typical well cross-bedded Pennsylvanian sandstone in the Eastern Interior coal basin.

teristic of the Pennsylvanian sediments above the New Burnside coals.

SEDIMENTARY STRUCTURES

The sedimentary structures of Pennsylvanian clastic sediments that are most prominent are associated with the silty and sandy sediments. It is convenient to consider these features in terms of major external structures (shown in outcrops) and minor internal structures (shown in cores).

Major External Structures

The arenaceous Pennsylvanian sediments of this area contain almost every type of major external sedimentary structure. These include cross-bedding, ripple marks, current fluting and drag grooves, current lineation, cut-and-fill, load casts, and slump structures.

Cross-bedding

Cross-bedding is the most prominent sedimentary structure. It is probable that no Pennsylvanian sandstone of any appreciable thickness and areal extent is without cross-bedding. It is especially abundant in the coarser grained sandstones.

The shapes of the cross-bedded units are best described in terms of length-to-width-to-thickness ratios. With large (greater than 10?) length-to-width ratios, the bottom surface of the crossbed is notably concave and is called "festoon" by some authors (pl. 1-A). With smaller length-to-width ratios (near unity?) the basal surface becomes sensibly flat and the term planar or torrential has been applied. A complete gradation appears to exist between planar and festoon cross-bedding.

In terms of size, cross-bedded units vary as much as 100 times (mostly in length and width) from micro-cross-bedding (the "rib and furrow" of some authors), which may be only a few inches wide and less than two feet long, to cross-bedded units that may be 20 to 40 feet wide and 80 to 120 feet long. Maximum thickness of cross-bedded sedimentation units is generally 1 to 4 feet, although some units are as much as 12 feet thick.

Regardless of scale, the foreset beds of these units are commonly convex in the up-current direction. They are noticeably so in those cross-bedded units with high length-to-width ratios (pl. 1-A).

Figure 7 shows diagrammatically a series of cross-bedded sedimentation units in a typical well cross-bedded Pennsylvanian sandstone.

Ripple marks

Although not as prominent as cross-bedding, ripple marks are probably even

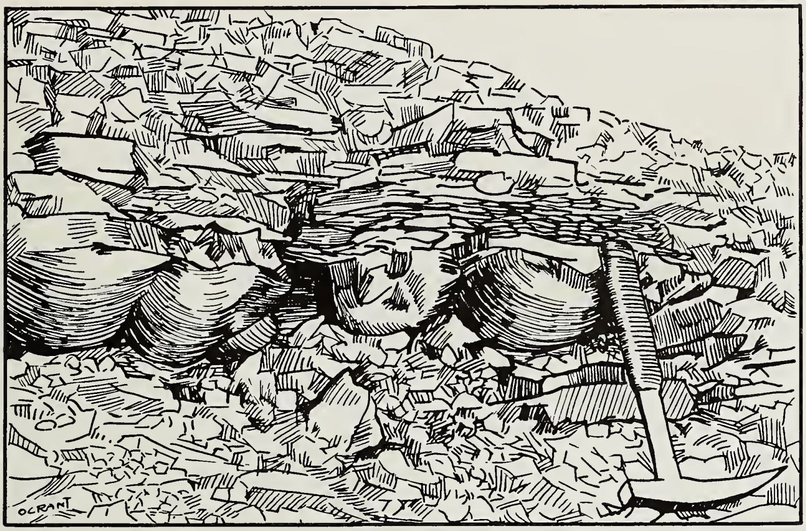


FIG. 8. — Load casts (drawn from a photograph) in thin-bedded Caseyville sandstone exposed in road cut along the east side of U. S. highway 45, approximately 5 miles north of Vienna in NE¼ SW¼ NW¼ sec. 14, T. 12 S., R. 3 E., Johnson County, Illinois.

more abundant. They generally are best seen in the thinner bedded, slabby, and finer grained sandstones or siltstones and are nearly always best exposed in creek beds.

Although gradations are probable, it is convenient to classify the ripple marks into three types: asymmetrical (current), symmetrical (oscillation), and interference (pls. 1-B, 2-A, and 2-B). Asymmetrical and interference ripples are the most common.

A fourth type of ripple mark, probably antidune bedding (Gilbert, 1914, p. 11-31) or regressive sand waves (Bucher, 1919, p. 165), was observed at only one locality in the Tradewater sandstone (pl. 3-A). Antidune bedding, the migration of sand waves in the up-current direction, is the response to a higher current velocity than that which produces ordinary ripples (Gilbert, 1914, p. 30-32). Although antidune bedding often can be found in glacial outwash sands near the ice front (rapid velocity changes), its preservation in most sands is rare because decrease of velocity is generally sufficiently slow so that down-current transport produces ordinary ripples rather than regressive sand waves.

Current fluting and drag grooves

Current fluting and drag grooves (pl. 3-B) also are present in this area but are not common. They are most likely to be found in the finer grained and thin-bedded sandstones. Current fluting results from the erosion produced by subparallel currents at the sediment interface. Drag grooves develop when currents drag debris across the sediment interface.

Current lineation

Current lineation also is a response to flow at the sediment interface. As shown in plate 4-A, the lineated structure can persist through a number of laminae. Current lineation, like current fluting, is best seen in the finer grained sandstones but is very rare.

Load casts

Figure 8 shows an unusually well developed series of load casts. Load casts generally are best seen in the thinner bedded, fine-grained sandstones that are not cross-bedded. They are commonly developed along specific horizons. They can occur either at the interface of sandstone beds or along sandstone-shale contacts. Load casts are an example of soft sediment deformation and result from the mechanical protrusion of the overlying into the underlying bed prior to consolidation. They may be oriented or unoriented.

Oriented or directional load casts, such as those in plate 4-B, were formed in similar manner except that the slope of the interface was sufficiently inclined so that flowage had a preferred direction. Directional load casts are very rare. The best examples have so far been found in the Caseyville sandstones.

Depending on the local slope of the sedimentation surface at or shortly after deposition, a complete gradation between directional and nondirectional load casts seems probable. The dominance of nondirectional rather than directional load casts throughout this entire 1800-foot Pennsylvanian section indicates that the depositional slope was never steep as in some geosynclinal flysch sequences.*

Cut-and-fill

Cut-and-fill structures are common throughout the entire section. Locally derived conglomerates often are associated with the largest of these structures.

Plate 5 shows an unusually fine example of a special type of cut-and-fill structure, here termed a "ripple scour." Such scours are ellipsoidal in outline, commonly gently concave upward, range in length from 2 to 6 feet, and often have ripple marks oriented at right angles to the long axes of the scour trough. Ripple scours have been observed only in the sandy sediments. They are present throughout the section. Commonly they are associated with the well cross-bedded, coarser, and generally ripple-marked sandstones. At individual outcrops, their long axes tend to be subparallel. Qualitative observation indicates that the long axes of ripple scours are commonly subparallel to the local cross-bedding direction.

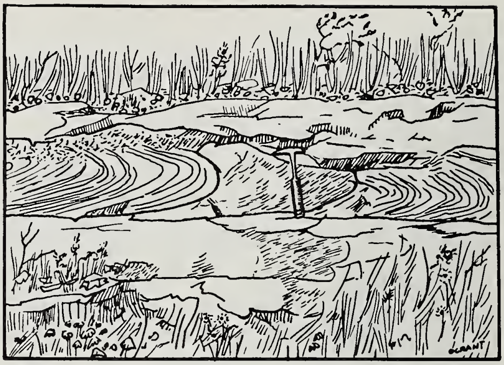


Fig. 9. — Overturned cross-bedding (drawn from a photograph) as exposed at the crest of the hill along the west side of Illinois highway 37, approximately one mile south of Goreville in NE¼ SE¼ SE¼ sec. 27, T. 11 S., R. 2 E., Johnson County, Illinois.

Plate 5 shows the salient features of their origin. Deposition of the underlying bed was followed by a subsequent thread of turbulence that eroded the elongate scour. The transverse ripples originated in the final stages of this erosion. Deposition of the overlying bed subsequently filled the ripple-scour trough. Ripple scours can be found at many outcrops, and at a few outcrops are the most abundant sedimentary structure.

Slump structures

Slump structures include overturned cross-bedding, convolute bedding, and small, free-gravity slides. Only overturned cross-bedding is relatively common, and a typical example is shown in figure 9. Overturning in the down-current direction prior to deposition of the overlying bed is inferred. At some places half a dozen or so sedimentation units exhibit more or less continuous overturned foreset beds over areas of a few hundred feet. Comparable structures in other cross-bedded rocks have been described by

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* Kuenen (1957) recently has described in detail morphologically similar features from the graywacke sandstones. He presented evidence for a primary erosional origin in addition to the "flowage" origin described above. Kuenen (1953b, p. 23-25) and Sanders (1957, p. 200) have presented helpful criteria to distinguish between these two different origins. Because these criteria are not always applicable, the term "oriented sole marking" has much to commend it. Sanders (1957, p. 199-200) also briefly reviews the rather confusing terminology on the subject.

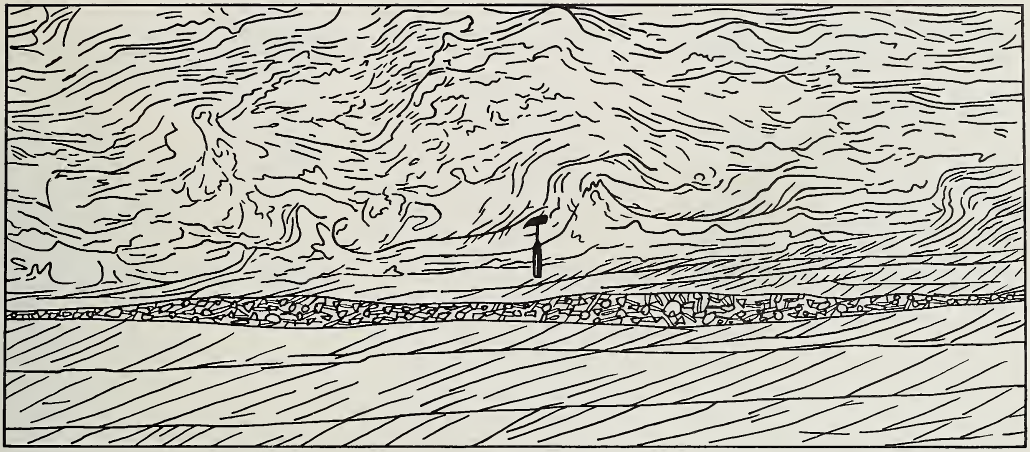

FIG. 10. — Convoluted bedding (drawn from a photograph) in the Delwood sandstone as exposed in the north side of an eastward-flowing tributary of Katy Ridge Hollow in SW¼ SE¼ SW¼ sec. 18, T. 11 S., R. 5 E., Pope County, Illinois.

Knight (1929, p. 74-78), Kiersch (1950, p. 939-941), Kuenen (1953a, p. 1051), Fuller (1955, p. 164) and others.

Convoluted bedding is present (fig. 10). It appears to be identical to that described by Rich (1950, p. 729-730) and Kuenen (1952, p. 32-33; 1953a, p. 1056-1058).

Slumped and folded beds of outcrop dimensions occur at two outcrops: one at the spillway of Crab Orchard dam in the SE¼ NW¼ NW¼ sec. 30, T. 9 S., R. 1 E., and one just south of the bridge over Crab Orchard Creek in the SE¼ NW¼ NE¼ sec. 2, T. 9 S., R. 1 W., Jackson County, in the vicinity of the DuQuoin monocline. Because the monocline marks the boundary between a rapidly subsiding basin and a more stable shelf, slide structures might be most abundant along this tectonic structure.

Soft-sediment slump structures of more extreme types such as sandstone balls, pull-aparts, and ptygmatic folding (Kuenen, 1949; Kuenen and Carozzi, 1953, p. 364) have not been observed. Their absence, along with the rarity of directional load casts, indicates that the slope of the sedimentation surface was very low.

MINOR INTERNAL STRUCTURES

Minor internal structures are best seen in diamond drill cores. They include disturbed bedding, animal burrows, and graded bedding.

Disturbed bedding (fig. 11) is best developed in siltstone-shale interlaminations, and generally occurs in zones less than one foot thick. Disturbed zones probably have several origins. They could have resulted from minor slumping, from deposition of the laminations on subsequently compacted plant debris, from animal burrows, or from mechanical distortion induced by the weight of an overlying sand body. It is not always possible to determine a specific origin. For example, neither animal burrows nor unusual amounts of carbonized plant compression are always present. Animal burrows are present but not conspicuous in cores.

Graded bedding in shale and siltstone is exceedingly rare in outcrops and cores. Silt-shale interlaminations with sharp contacts (fig. 11; pls. 7 and 8) rather than graded bedding, are typical. Such interlaminations are well developed throughout the section and in many instances can be considered as evidence of proximity to a zone of high current velocity and turbulence; that is, they are proximal to sand bodies.

Observation of outcrops indicates that the silty portion of these interlaminations are small, often isolated ripples of silt or

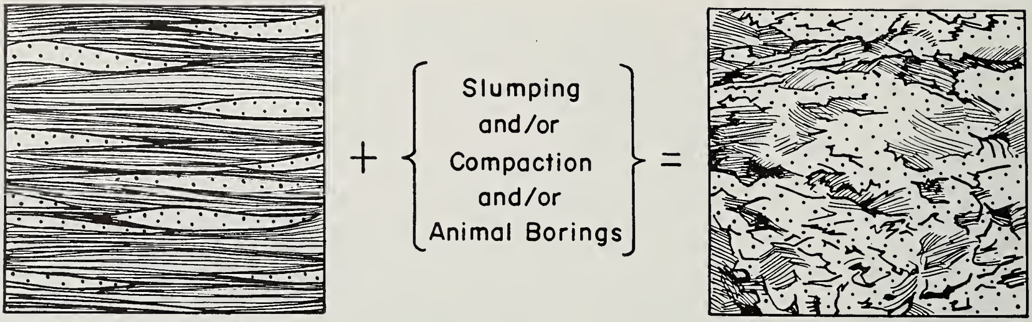

Fig. 11. — Diagrammatic representation of the origin of disturbed bedding.

fine sand that were migrating (commonly with markedly preferred transport directions) across a clayey bottom. As such, these ripples provide a qualitative proof of Hjulström's law (Hjulström, 1939), which states that higher velocity is required to erode clay-sized particles than to transport silt and fine sand.

Directional Structures

Another way of considering the sedimentary structures is based on their usefulness for determining direction of current flow. In various sedimentary associations, cross-bedding, ripple marks, current lineation, current fluting, load casts, drag grooves, and slump structures all have been used successfully, either in combination or singly, for determining the local and/or regional direction of sediment transport. Depending broadly on the depositional environment, one or two of the directional structures will be dominant, and even though the others are present, the requirements of widespread occurrence, ease of measurement, and simplicity of interpretation will nearly always necessitate prime emphasis upon the dominant structures. This is precisely the condition prevailing in the Pennsylvanian sediments. Table 2 shows the abundance of the directional structures of these sediments.

Slump structures are not only less directionally definitive, but in these rocks are far too rare to be useful. Although current fluting, drag grooves, directional load casts, and current lineation structures are definitive, they are not sufficiently well developed to be useful. Problems of measurement and an apparent large local variability make the use of ripple marks undesirable although they are abundant. In contrast, cross-bedding, also abundant, is amenable to easy sampling. It has been studied previously in the Pennsylvanian rocks of the Eastern Interior coal basin (Olson and Potter, 1954; Potter and Siever, 1956, part I), and has significance for regional source-area determination.

One of the primary objectives of our field work was to estimate the direction of transport of the post-Caseyville sediments. This was done by measuring the dip direction of one foreset bed in two sedimentation units at each of 86 outcrops. For the method of sampling, its practical compromise with strictly random sampling, and the statistical treatment of the data, see Olson and Potter (1954) and Potter and Siever (1956, part I).

The measured cross-bedded outcrops of the area for the sediments above the Caseyville group are shown on figure 12 along with two directional distribution diagrams, one for the Caseyville group in southern Illinois, and the other for the post-Caseyville sandstones of the Williamson County area. Table 3 gives the statistical computations. The grand mean of two levels of sampling for the post-Caseyville sandstones of this vertical profile is 201° and 90 percent confidence limits are ±12 degrees.

Table 2.—Optimum Occurrence of Sedimentary Structures and Sandstone Types

	Sedimentary structure	Optimum occurrence	Sandstone type	
			Orthoquartzites	Subgraywackes
Directional structures	Cross-bedding	Thicker, coarse-grained "channel" sandstones	Abundant	Abundant
	Ripple marks	Thin-bedded, slabby sandstones	Abundant	Abundant
	Ripple scour	Thicker, coarse-grained sandstones	Common	Common
	Current lineation	Thin-bedded, fine-grained sandstones	Rare	Rare
	Current fluting and drag grooves	Thin-bedded, fine-grained sandstones	Rare	Rare
	Load casts	Thin-bedded sandstones or interbedded shales and sandstones	Very rare	Very rare
	Overturned cross-bedding	Thicker, coarse-grained sandstones	Common	Common
	Cut-and-fill	Thicker, "channel" sandstones	Common	Common
Nondirectional structures	Load casts	Thin-bedded sandstones or interbedded shales and sandstones	Common	Common
	Convoluted bedding	Observed in outcrop and rare in cores. Soft sediment deformation not tied to any specific occurrence	Rare	Rare
	Disturbed bedding	Best seen in siltstone-shale interlaminations and caused by animal borings, compaction and slumping	Rare	Rare
	Graded bedding	In some of the foresets of cross-beds and very rarely in some shales and fine siltstones	Very rare	Very rare
	Desiccation marks, sandstone balls, pull-aparts, and ptygmatic folding		Not observed	Not observed

Additional Significance

That the silty and sandy sediments of this Pennsylvanian sequence were deposited in shallow and turbulent waters is made clear by the data in table 2. The sedimentary structures of these rocks correspond roughly to those of fluvial, littoral, and shallow marine shelf deposits. The sedimentary structures of both beaches and sand dunes appear to be absent, however. It is also evident from table 2 that turbidity currents played no significant role in the deposition of these sediments.

Another conclusion to be drawn from our field study of the sedimentary structures is that both the clean quartz sandstones of the Caseyville (orthoquartzites) and the micaceous and argillaceous sandstones above the New Burnside coals (subgraywackes) have essentially identical types and abundances of sedimentary structures. The lesser degree of sorting of the subgraywackes was not sufficient to produce major contrasts in sedimentary structures.

PETROLOGY

The ultimate objective of our petrologic study was to isolate and assess, in terms of both mineralogy and texture, the effects of provenance and environment. To attain this goal, however, it was necessary to take three preliminary steps. First, we wished to determine the

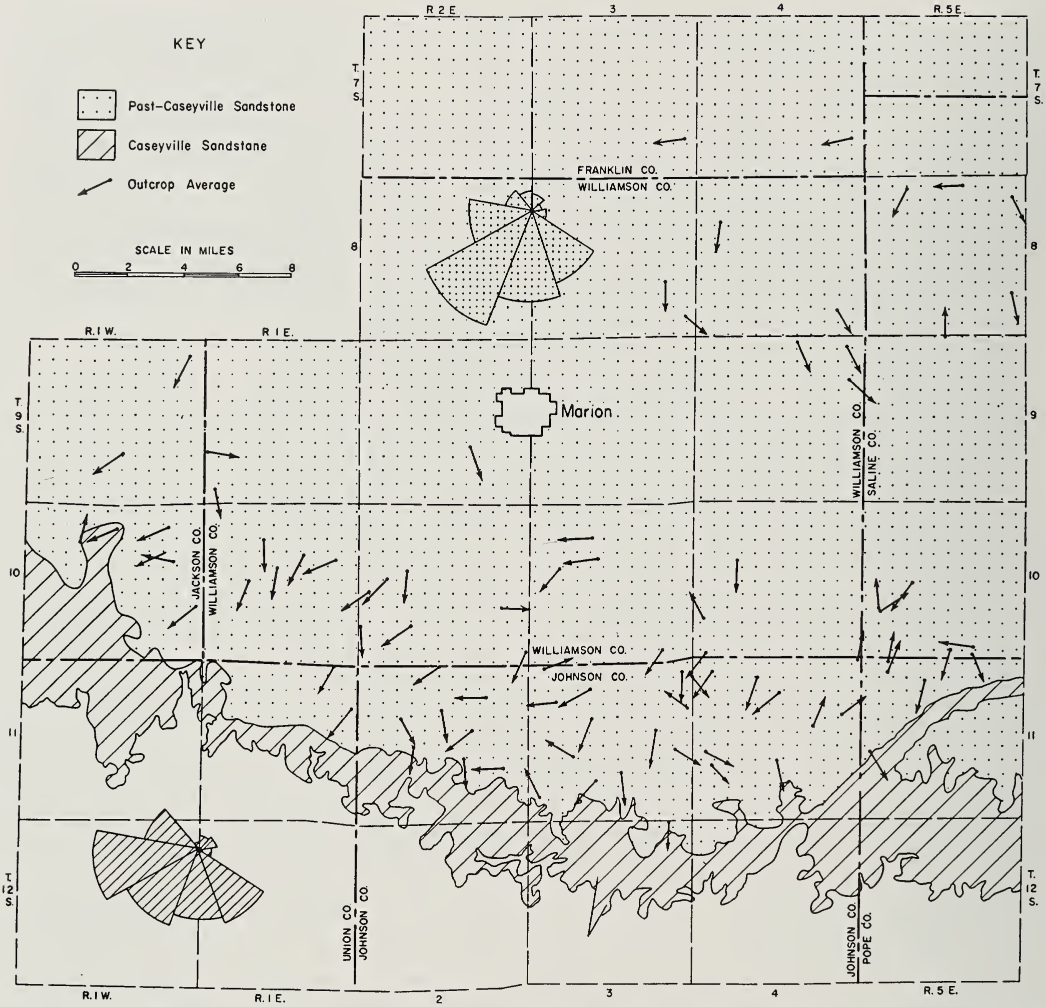

Fig. 12. — Cross-bedding and directional distribution of post-Caseyville sandstones (172 measurements in 86 outcrops) and Caseyville outcrop and directional distribution (204 measurements in 68 outcrops in southern Illinois).

stratigraphic positions of the major mineral associations. Second, we wished to characterize, both qualitatively and quantitatively, the composition of these mineral associations. Finally, we wished to assess the role that post-depositional diagenesis has played in producing present mineralogy and texture. Because of the dominance of clastics in the area studied, primary emphasis was placed on the sandstones and shales, with the less prevalent limestones receiving comparatively little attention.

The greatest number of samples was obtained from a 2140-foot diamond drill core in the NE¼ NE¼ NW¼ sec. 12, T. 8 S., R. 3 E., Williamson County. This complete core, in the possession of the Survey since 1923, was partially sampled for sandstones by Raymond Siever in 1949 and subsequently by us for both sandstones and shales. Outcrop samples of sandstones and shales supplemented those obtained from the core. The appendix gives the stratigraphic position and location of the samples.

Sandstones

Petrographic study included examination of both thin sections and heavy

Table 3.—Variance Components for the Post-Caseyville Pennsylvanian Cross-bedding in and Near Williamson County, Illinois (Caseyville Group excluded)

A. Summary computations

$\sum_{i=1}^{86}\sum_{j=1}^{2} X_{ij}$	$\sum_{i=1}^{86}\sum_{j=1}^{2} X^2_{ij}$	$\sum_{i=1}^{86}(\sum_{j=1}^{2} X_{ij})^2$
34,678	7,843,132	7,779,961

86 outcrops, each with two observations

B. Analysis of variance

	Sums of squares	Degrees of freedom	Mean square	Expected value
Outcrops (i)	778,292	85	9156.4	$\sigma_i^2 + k\sigma_j^2$
Foresets (j)	63,171	86	734.5	σ_j^2

C. Components of variance

	Mean squares				
	Higher	Lower	Difference	Sample	Component
Outcrops (i)	9156.4	734.5	8421.9	2	4210.9
Foresets (j)		—	734.5	1	734.5

minerals as well as determination of the clay mineralogy of the sandstones' detrital matrix. Less emphasis was given to study of texture.

Modal estimates of 36 thin sections were made by point counter using 200 counts per slide (table 4). A corresponding number of heavy mineral separations were made (table 5). The size fraction 0.062 to 0.500 millimeters was used for study of heavy minerals. On each slide 100 transparent, nonmicaceous grains were counted. The proportions of micaceous minerals and round tourmaline grains also were estimated from counts of 100 grains. Round tourmaline was defined as that whose roundness was greater than or equal to six-tenths on the Krumbein (1941, p. 68) chart. Some samples were boiled in concentrated HCl for 30 to 60 seconds to remove iron oxides. Only apatite, discovered after about half the separations were made, was affected by the acid treatment. Figure 3 shows graphically plots of mineralogical composition and tourmaline roundness versus stratigraphic position. Variation in mineralogy between samples, especially for the heavy minerals, is largely the result of granular variation.

Vertical variation in petrographic properties closely coincides with the vertical variation in megascopic properties summarized in table 1. Megascopically and microscopically, the contrast between the Caseyville and the transition group is much more distinct than the contrast above and below the New Burnside coals. Undoubtedly the upper boundary of the transition zone is very gradational. We selected the New Burnside coals as the top of the transition zone because their stratigraphic position coincided with the position of greatest over-all lithologic contrast.

If abundance of matrix clay and feldspar are considered as the most genetically significant classifying criteria, there are three petrographic groups: a lower group coinciding with the Caseyville, a transition group ranging from the Caseyville to the New Burnside coals, and the argillaceous, micaceous sandstones above the New Burnside coals.

CASEYVILLE SANDSTONES

The average modal, detrital, and source-area components of the Caseyville sandstones in Williamson County are given in table 6. The average detrital composition of the 7 samples from Williamson County is almost identical to that of the 40 samples (nearly all from outcrops) of the Caseyville and Mansfield sandstones from the Eastern Interior coal basin studied by Siever and Potter (1956). Plate 6 shows both the hand specimen and microscopic appearance of the Caseyville sandstones.

Mineralogically, these rocks consist mainly of quartz and secondary carbonate. Feldspar, matrix clay, and micaceous minerals are rare. In the absence of carbonate, the quartz grains form a tightly welded interlocking mosaic. Authigenic

TABLE 4.—MODAL COMPOSITION OF PENNSYLVANIAN SANDSTONES

Sample no.	Quartz	Clay	Carbonate	Feldspar	Mica	Chert	Rock fragments	Misc.
Subgraywacke group								
330	64.0	23.0	0.0	5.5	2.0	0.0	4.0	1.5
301	57.0	26.0	0.0	8.0	3.5	0.5	2.0	3.0
300	36.0	12.0	35.0	3.0	2.5	1.0	9.0	1.5
10	56.5	25.5	2.0	3.0	6.5	0.0	2.0	4.5
290	64.5	19.0	4.5	2.5	4.0	0.0	2.0	3.5
11	63.5	18.5	5.5	5.0	2.5	0.5	2.5	2.0
12	39.0	4.5	50.0	3.0	1.5	0.5	0.5	1.0
328	59.0	22.5	0.0	8.5	4.5	1.5	1.0	3.5
329	63.5	17.5	11.0	3.0	2.0	1.0	0.0	2.0
13	55.0	4.0	30.0	4.5	2.5	0.5	2.0	1.5
291	55.0	21.0	0.0	5.0	10.5	0.0	4.5	4.0
14	47.0	22.0	23.0	1.0	4.0	0.0	2.0	1.0
379	74.5	16.0	0.0	5.0	1.5	0.0	2.5	0.5
292	66.0	24.5	0.0	4.0	2.0	0.5	2.5	0.5
293	56.0	4.5	29.0	3.0	1.5	0.0	4.5	1.5
16	54.0	13.0	21.0	1.5	6.5	0.0	1.0	3.0
294	67.0	25.5	0.0	1.5	2.0	1.0	2.5	0.5
303	64.0	21.0	0.5	3.0	5.0	0.5	2.0	4.0
299	56.0	21.5	5.0	6.0	3.0	0.0	7.0	1.5
Transitional group								
17	65.0	15.5	1.5	8.0	2.5	2.0	5.5	0.0
18	73.5	17.0	0.0	3.0	0.5	0.0	4.0	2.0
39	57.5	0.5	35.5	2.0	1.0	0.0	0.0	3.5
20	88.5	5.0	0.0	4.5	1.0	0.5	0.5	0.0
21	81.0	10.5	2.0	2.0	1.0	0.0	2.5	1.0
38	66.5	10.5	18.0	1.5	0.0	0.5	2.0	1.0
22	76.5	9.5	9.5	1.0	2.5	0.0	1.0	0.0
23	89.0	7.5	1.0	0.0	1.0	0.0	1.0	0.5
24	89.0	9.0	0.5	0.0	0.0	1.0	0.0	0.5
25	47.5	0.0	49.5	0.0	0.0	1.5	0.0	1.5
Orthoquartzitic group								
295	88.0	2.5	4.5	4.0	0.0	1.0	0.0	0.0
40	73.5	0.0	26.0	0.5	0.0	0.0	0.0	0.0
26	71.5	1.0	27.0	0.0	0.0	0.0	0.0	0.5
41	88.0	8.0	0.0	1.0	0.0	1.5	1.5	0.0
42	66.5	1.0	29.0	0.5	0.0	0.0	3.0	0.0
27	73.5	1.0	24.0	0.0	0.0	0.5	1.0	0.0
28	95.0	3.5	1.5	0.0	0.0	0.0	0.0	0.0

quartz overgrowths are common and in some slides may be the dominant cement.

The secondary carbonate consists of both clear anhedral single crystals that may encompass portions of as many as three or four detrital quartz grains, and brown iron carbonate (siderite). The siderite is disseminated as small (20 to 40 microns), globular, anhedral crystals between the larger detrital grains. In the less than 2-micron fraction obtained from these sandstones, siderite is much more abundant than calcite. In core samples, carbonate was found to form as much as

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EXPLANATION OF PLATE 1

A.—Cross-bedding exposed at the spillway of Crab Orchard Lake in the SE¼ NW¼ NW¼ sec. 30, T. 9 S., R. 1 W., Jackson County, Illinois.

B.—Asymmetrical current ripples in Tradewater sandstone obtained from a roadside ditch in NE¼ NE¼ SE¼ sec. 30, T. 10 S., R. 3 E., Williamson County.


A


B

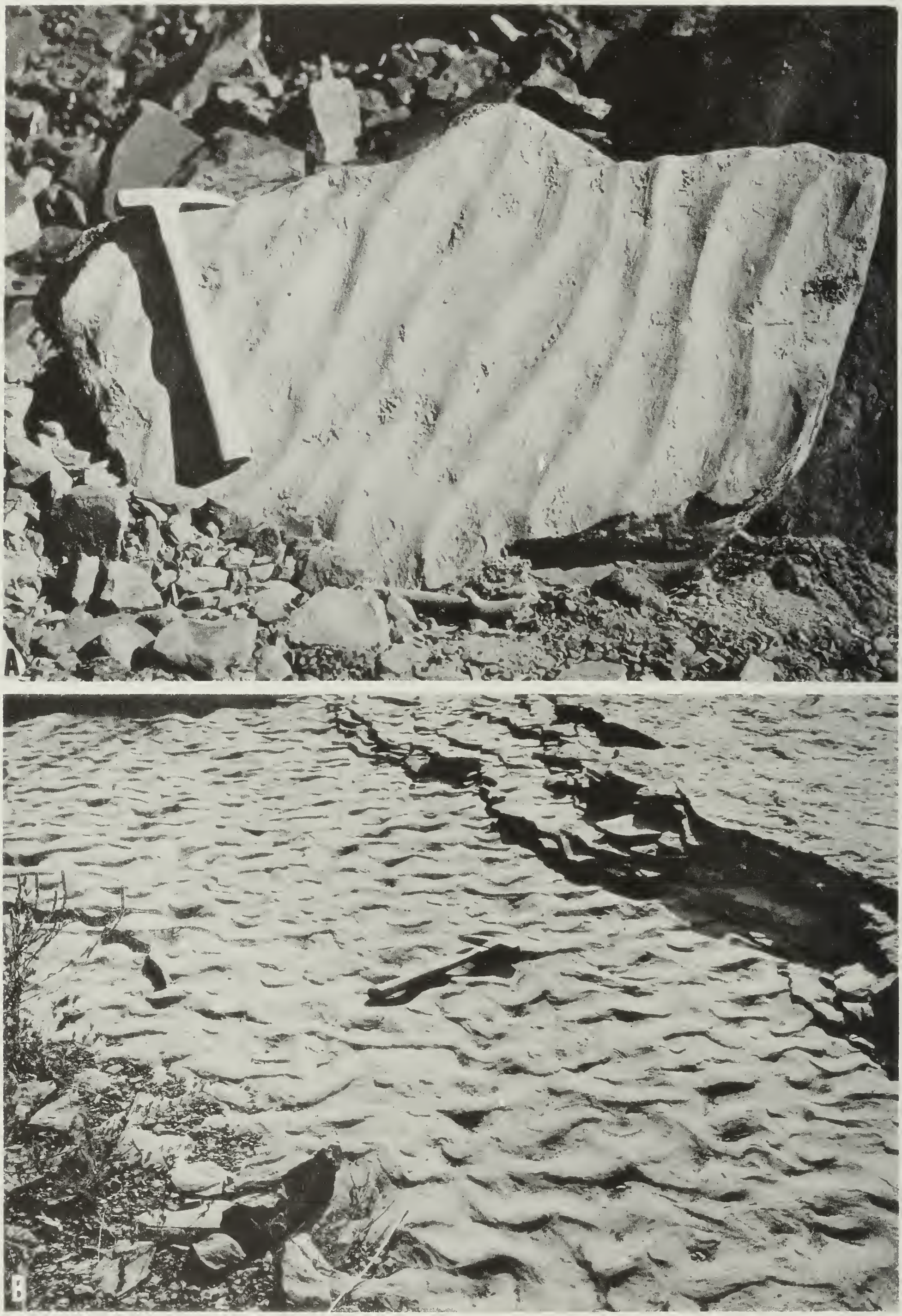

A
B

TABLE 5.—HEAVY MINERALS, TOURMALINE ROUNDNESS, AND MICAS IN PENNSYLVANIAN SANDSTONES (0.062 to 0.5 mm.)

Sample no.	Heavy minerals (percent)								Tourmaline roundness (percent)		Micas (number)		
	Zircon	Tourmaline	Rutile	Garnet	Anatase	Collophane	Apatite	Barite	Round	Nonround	Biotite	Chlorite	Muscovite
330	39	58	3	0	0	0	0	0	0	100	0	0	100
301	15	57	3	13	6	6	P*	0	0	100	1	3	45
300	55	22	2	19	1	0	0	0	1	99	4	6	30
10	25	75	0	0	0	0	P	0	8	92	11	41	48
290	33	67	0	0	0	0	P	0	0	100	5	38	57
11	61	35	0	4	0	0	P	0	0	100	5	13	82
12	55	35	1	9	0	0	0	0	1	99	6	24	70
328	52	46	2	0	0	0	P	0	0	100	0	1	99
329	2	81	4	13	0	0	P	0	1	99	0	21	3
13	24	70	1	2	2	0	0	P	0	100	0	23	77
291	6	92	0	1	0	0	P	0	2	98	1	24	75
14	63	34	3	0	0	0	P	0	1	99	0	37	64
379	40	55	1	0	4	0	0	0	1	99	0	0	16
292	5	93	2	0	0	0	P	P	2	98	4	1	41
293	92	8	0	0	0	0	0	0	3	97	3	49	47
16	63	31	4	0	2	0	P	0	0	100	6	46	48
294	3	96	1	0	0	0	P	0	0	100	2	0	52
303	48	49	3	0	0	0	P	0	2	98	1	1	98
299	64	36	0	0	0	0	P	0	0	100	10	64	26
18	51	43	6	0	0	0	0	0	29	71	0	7	93
39	71	26	1	1	0	1	P	0	0	100	0	24	76
20	53	43	3	1	0	0	0	0	2	98	0	9	91
21	52	42	4	0	2	0	0	0	3	97	0	14	86
38	73	26	1	0	0	0	P	0	17	83	11	62	27
22	85	8	3	0	4	0	0	0	19	81	5	38	58
23	77	21	2	0	0	0	P	P	40	60	0	1	34
24	93	4	2	0	0	1	0	0	19	81	0	0	16
25	71	19	4	0	6	0	0	0	19	81	0	4	96
295	10	62	3	0	24	1	0	P	33	67	—	—	—
40	63	35	2	0	0	0	0	0	44	56	0	1	17
26	54	44	0	0	2	0	0	0	31	69	0	0	2
41	69	23	2	0	6	0	0	0	48	52	0	2	18
42	87	10	3	0	0	0	0	0	27	73	0	1	7
27	51	45	4	0	0	0	0	0	33	67	—	—	—
28	68	29	2	0	1	0	0	0	31	69	1	0	31

* P indicates mineral is present.

30 percent of the sample. Where carbonate is present in abundance, replacement of quartz generally is extensive. Barite is a minor cementing agent.

Aggregates of small (2 to 10 microns) pseudo-hexagonal kaolinite crystals are present. Detrital micas are present but are not abundant in either hand specimen, thin section, or heavy-mineral slide. Counts in heavy-mineral slides show muscovite to be much more abundant than either chlorite or biotite (fig. 13). The transparent heavy minerals are dominantly zircon and tourmaline, with rutile, anatase (both detrital and authigenic), and collophane as minor components. As shown by the almost complete dominance of quartz, zircon, tourmaline, and musco-

EXPLANATION OF PLATE 2

A.—Symmetrical oscillation ripple marks in fine-grained DeKoven sandstone, exposed in the Will Scarlet strip mine approximately 3 miles northwest of Stonefort, Saline County, Illinois.

B.—Interference ripple marks exposed in lower Tradewater sandstone in a creek bed in northwestern Johnson County, Illinois.

Table 6.—Average Sandstone Composition

Rock type	Quartz	Detrital matrix	Carbonate	Feldspar	Mica	Chert	Rock fragments	Misc.	No. of samples
				A. Modal analyses					
Subgraywackes	57.8	17.8	11.4	4.0	3.6	0.3	2.9	2.2	19
Transition group	73.4	8.5	11.7	2.2	1.0	0.4	1.9	1.0	10
Orthoquartzites	79.4	2.4	16.0	0.9	0.0	0.6	0.7	0.1	7
				B. Detrital components					
Subgraywackes	65.3	20.1	—	4.5	4.1	0.3	3.2	2.5	19
Transition group	83.0	9.7	—	2.5	1.1	0.4	2.1	1.1	10
Orthoquartzites	94.5	2.9	—	1.0	0.0	0.8	0.8	0.1	7
				C. Source area components					
Subgraywackes	81.6	—	—	5.7	5.1	0.4	4.1	3.1	19
Transition group	92.0	—	—	2.8	1.2	0.3	2.4	1.3	10
Orthoquartzites	97.3	—	—	1.1	0.0	0.7	0.9	0.1	7

vite among the detrital minerals, the Caseyville rocks are mineralogically very mature.

Caseyville sandstones have a number of interesting textural features (Biggs and Lamar, 1955, table 4). The conglomeratic quartz granules and pebbles, although conspicuous to the eye, affect the size distribution very little. Not only were quartz granules and pebbles present in only approximately one-fourth of Biggs and Lamar's (1955, table 4) samples, but where present they generally constituted less than one percent of the entire sediment. Although median sizes range from 0.096 mm. (very rare) to as large as 0.690 mm. (very rare), values between 0.150 mm. and 0.350 mm. are typical. The typical Caseyville sandstones are thus medium- to fine-grained.

We used the data of Biggs and Lamar (1955, table 4) to compute phi sorting coefficients (Inman, 1952) for 17 samples with median sizes between 0.19 to 0.38 mm. (table 7). For these samples, phi sorting coefficients range from 0.944 to 0.329 and average 0.583, indicating that the average Caseyville sandstone is well sorted.

Because of authigenesis and the effects of pressure welding, roundness estimates based on either loose or thin-sectioned quartz grains are not satisfactory. Roundness of tourmaline determined from heavy-mineral slides provides such an estimate. The proportion of round tourmaline (0.6 or greater on the Krumbein

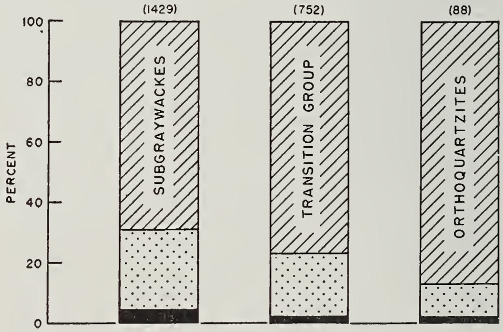


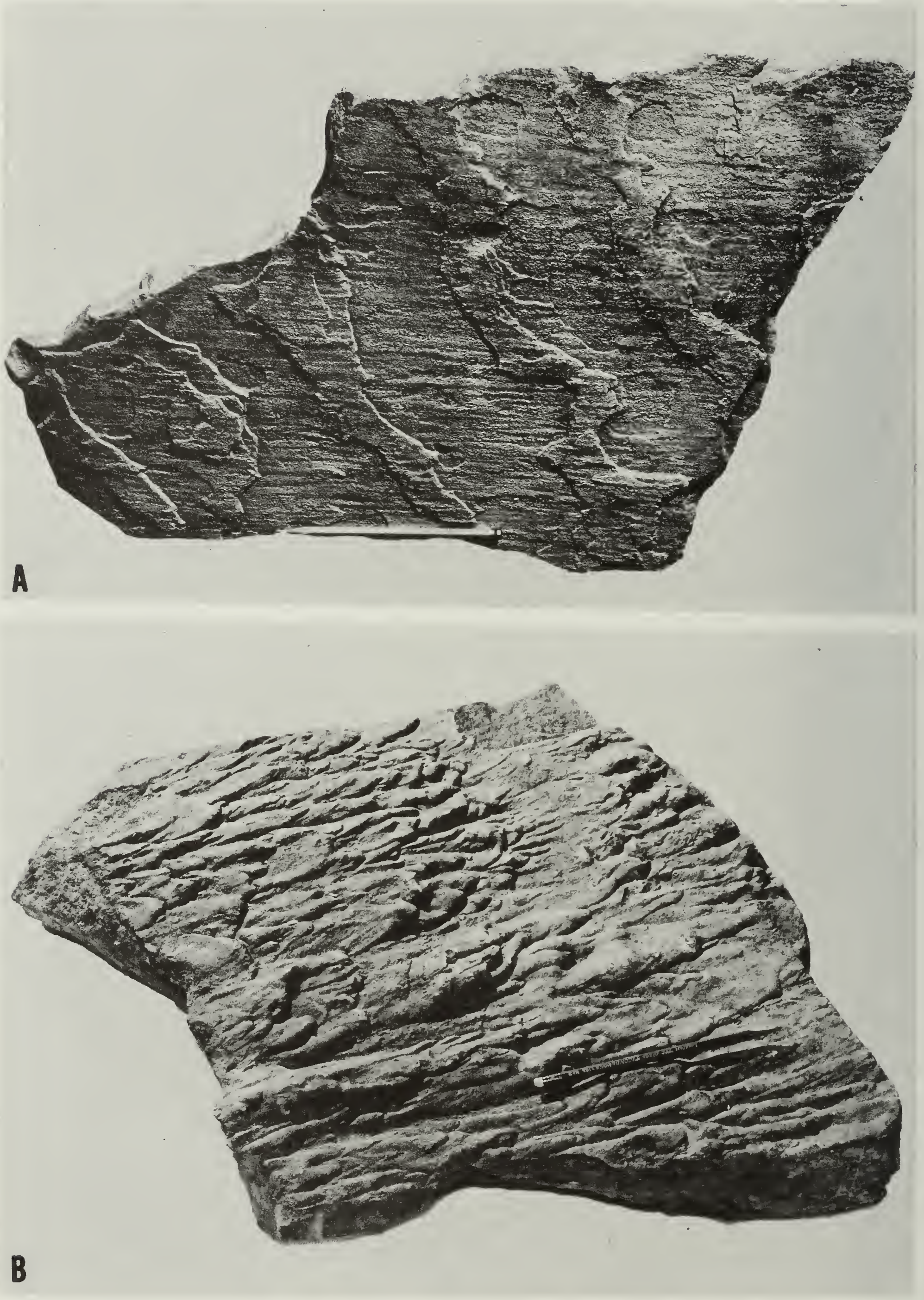
Fig. 13.—Contrasting abundances of sand-fraction muscovite (ruled), chlorite (stippled), and biotite (black) in Pennsylvanian sandstones. Number of particles counted shown in parentheses.

EXPLANATION OF PLATE 3

A.—Probable antidune bedding exposed in a small creek bed in NW¼ NE¼ NE¼ sec. 6, T. 10 S., R. 1 W., Jackson County, Illinois.

B.—Current fluting and drag grooves shown on underside of thin-bedded and fine-grained McLeansboro (Trivoli?) sandstone from northeastern Williamson County, Illinois.


B


A
B

chart, 1941, p. 68) was determined for the size range 0.062 to 0.5 mm. because 1) an abrasion index for the entire sediment rather than a restricted size range was desired, and 2) good hydraulic sorting made choice of a single size grade difficult.

Siever and Potter (1956) showed that in the basal Pennsylvanian sandstones of the north-central states there was no association between tourmaline size and roundness in the size range 0.062 to 0.5 mm. That is, increase in size was not accompanied by increase in roundness comparable to that expected if all the grains had had the same abrasion history. This conclusion is confirmed in a different manner by the three cumulative curves of figure 14, which show that roundness does not depend on size. The coarser grained Pennsylvanian subgraywacke from above the New Burnside coal contains only 2 percent round grains, but the finer grained (Pennsylvanian) orthoquartzite and the St. Peter (Ordovician) sandstones have 42 to 97 percent round grains respectively. In these sediments, therefore, tourmaline roundness is almost entirely a function of previous abrasion history rather than an expression of the universal dependence of roundness on size. Approximately 35 percent of the tourmaline grains of Caseyville sandstone are round.

Table 7.—Comparative Sorting (ϕ) for Pennsylvanian Subgraywackes and Orthoquartzites and the St. Peter (Ordovician) Sandstone (1 phi unit, 0.38 to 0.19 mm)

Pennsylvanian		St. Peter sandstone[2]
Subgraywackes	Orthoquartzites[1]	
.822	.641	.514
.930	.527	.628
.660	.421	.758
.509	.916	.629
.687	.699	.522
.842	.526	.801
.894	.329	.680
.973	.944	.405
.819	.379	.636
.763	.475	.502
.963	.934	.598
.851	.692	.383
.575	.424	.475
.588	.655	.427
	.408	.531
	.493	.662
	.463	.545
		.783
		.649
		.487
		.631
		.679
		.429
Average $\overline{x}_1 = .769$	$\overline{x}_2 = .583$	$\overline{x}_3 = .581$

[1] Data from Biggs and Lamar (1955, table 4).

[2] Data from Lamar (1927, table 10) and Giles (1930, table 5).

TRANSITION SANDSTONES

The sandstones of the transition group average, on a carbonate-free basis (table 6), 83 percent quartz and 9.7 percent clay matrix. Less roundness and increased clay matrix, feldspar, micas, and rock fragments (mostly locally derived) show these sandstones to be appreciably less mature than those of the Caseyville. Throughout much of this zone the quartz grains appear to be less well rounded than those of the Caseyville.

The feldspars consist of both fresh and weathered microcline, orthoclase, and plagioclase. Unlike the sandstones of the Caseyville group, feldspar was positively identified in the less than 2-micron fraction of all but one of the sandstones. Although there is little increase in biotite, chlorite appears to be somewhat more abundant (fig. 13). A companion increase in immature heavy minerals does not occur. Zircon and tourmaline remain the dominant species and garnet, anatase,

EXPLANATION OF PLATE 4

A.—Current lineation in thin-bedded and fine-grained Caseyville sandstone exposed in creek bed in NE¼ NW¼ NW¼ sec. 32, T. 11 S., R. 5 E., Pope County, Illinois. Current lineation persists through a series of laminations.

B.—Underside of basal Caseyville orthoquartzitic sandstone showing unusual development of oriented load casts. Specimen obtained above the Kinkaid limestone from along the north-south road in NE¼ NW¼ sec. 31, T. 11 S., R. 2 E., Johnson County, Illinois, about ⅜ of a mile north of the Cedar Grove church.

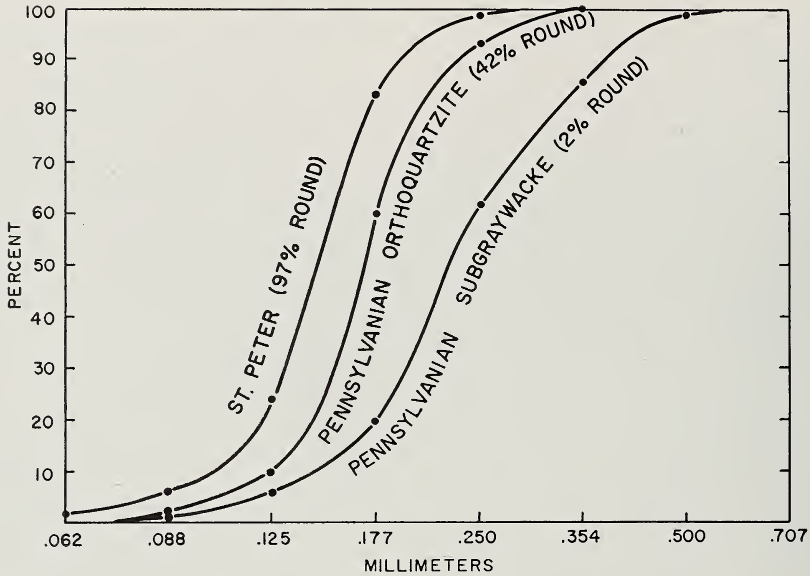


Fig. 14. — Cumulative curves of counts of 100 tourmaline long axes and percentage of round tourmaline grains. Note that the finer-grained sandstones have more round grains.

and collophane are all in minor abundance. Apatite is present, however, and its typical form is that of subrounded, broken, and fractured grains. Because apatite is rather brittle, disaggregation may have produced the fractured grains. The opaque heavy minerals include pyrite (generally the most abundant), magnetite, and ilmenite.

The sandstones of the transition group have both precipitated and detrital matrix cements. Thin sections show calcite and siderite to be the dominant mineral cements, with siderite probably more abundant than calcite. In the less than 2-micron fraction, siderite is also the more abundant. Siderite is especially prominent in the sandstones of the lower Tradewater group — the Grindstaff, Delwood, and Murray Bluff. It typically forms small (30 to 40 microns) anhedral crystals that partially fill the space between the framework fraction. The siderite cement can be so abundant that some core specimens have a dull, brownish-red cast. In outcrop, leaching and oxidation of the siderite impart a prominent reddish, ferruginous appearance to these sandstones.

The detrital matrix cement of the transition group sandstones differs in abundance, but not in kind, from that of the higher sandstones. Its properties are essentially those described in detail for the higher sandstones.

The sandstones of the transition group are texturally somewhat less well sorted than those of the Caseyville. Median sizes are broadly similar to those of the nonconglomeratic Caseyville sandstones. In terms of tourmaline abrasion, the grains are more angular (fig. 3); only some 15 percent of the tourmalines are well rounded.

Under the microscope as well as in hand specimen, the sandstones of the transition zone are more akin to those above the New Burnside coals than to the Caseyville sandstones.

SANDSTONES ABOVE THE NEW BURNSIDE COAL

Sandstones above the New Burnside coals form a very homogeneous group. Greater clay matrix and more feldspar, mica, and rock fragments indicate that these sands are the most immature of the

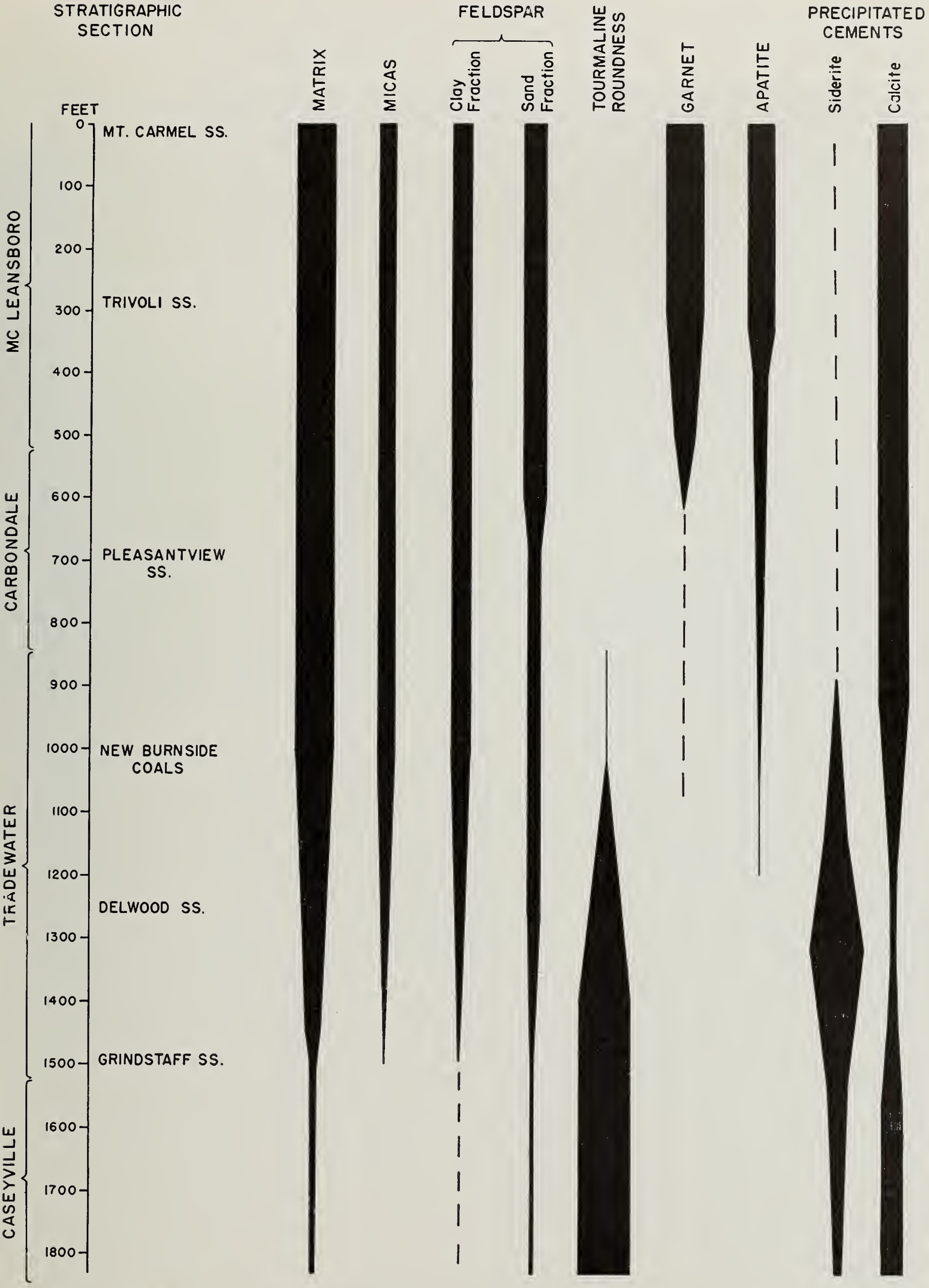


FIG. 15. — Diagrammatic summary of vertical variation of sandstone properties. Compare with figure 3 and table 8.

three groups (table 6). Plate 6 shows their hand-specimen and microscopic appearance.

An abundant detrital matrix probably is their most distinctive feature. As much as 26 percent clay matrix was observed. In contrast, the maximum amount of feldspar was only 8.5 percent. As in the transition sandstones, the three major types of feldspar are present and are both fresh and weathered. Feldspar was identified in the less than 2-micron fraction of all but one of these sandstones.

Although muscovite remains dominant, there is an increase in biotite and chlorite (fig. 13). Much of the detrital chlorite contains magnetite inclusions suggesting an alteration from biotite. With the exception of more abundant garnet and apatite, the nonopaque heavy minerals are essentially the same as in the transition group. Garnet becomes a significant element in the heavy-mineral suite at approximately the level of the Pleasantview sandstone. Apatite generally is persistent throughout the entire group. As in the transition group, the common opaque minerals are pyrite, magnetite, and ilmenite. Pyrite was observed in every slide.

The cementing agents of the sandstones consist of both detrital and precipitated mineral cements. The detrital matrix is composed mainly of silt and clay-sized quartz, clay minerals (micas), and authigenic pyrite. Authigenesis in this detrital matrix is apparent. Authigenic micaceous minerals are present in the matrix and marginally replace some of the larger detrital quartz and feldspar grains of the framework fraction. Aggregates of small (2 to 10 microns) pseudohexagonal kaolinite crystals that sometimes reach the size of the sand grains can be found in almost every slide. Authigenic quartz overgrowths occur but appear to be less abundant than in the Caseyville sandstones. Probably because of both compaction and authigenesis, the detrital character of fragments of locally derived siltstone often is difficult to distinguish from the detrital matrix.

In contrast to the Caseyville and transition sandstones, the younger sandstones have calcite as the dominant carbonate, as revealed in both thin section and in the less than 2-micron fraction. In thin section, calcite occurs as both large and small single and aggregate anhedral crystals. Siderite is present, but not abundantly, and it commonly forms small anhedral grains. Barite is a minor cementing agent. The typical hand-specimen and thin-section appearance of these rocks is shown in plate 6. In both hand specimen and thin section, the contrast between the Caseyville and higher sandstones is striking.

The higher sandstones are medium- to fine-grained in texture. When comparison is restricted to the size range 0.19 to 0.38 mm., phi sorting coefficients range from 0.509 to 0.973 and average 0.769 (table 7). These sandstones are thus appreciably less well sorted than those of the Caseyville.

Qualitatively, the quartz grains of the higher sandstones are poorly rounded. Quantitatively, the abundance of round tourmaline grains is negligible, being only 2 percent.

SIGNIFICANT VERTICAL VARIATION IN PETROGRAPHIC PROPERTIES

The above petrographic description shows the degree to which a number of the more significant petrologic measures are interrelated. Both the interrelationships of these properties and their vertical stratigraphic variation are diagrammed in figure 15. Although not completely coincident, abundance of detrital matrix, feldspar, micas, angular tourmaline, and

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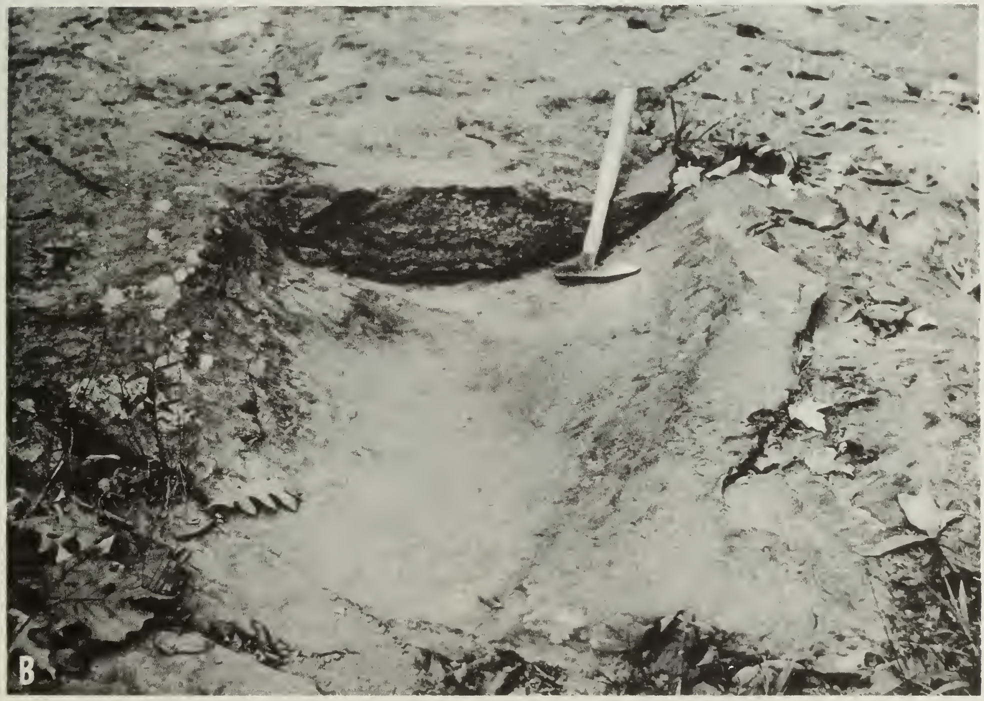
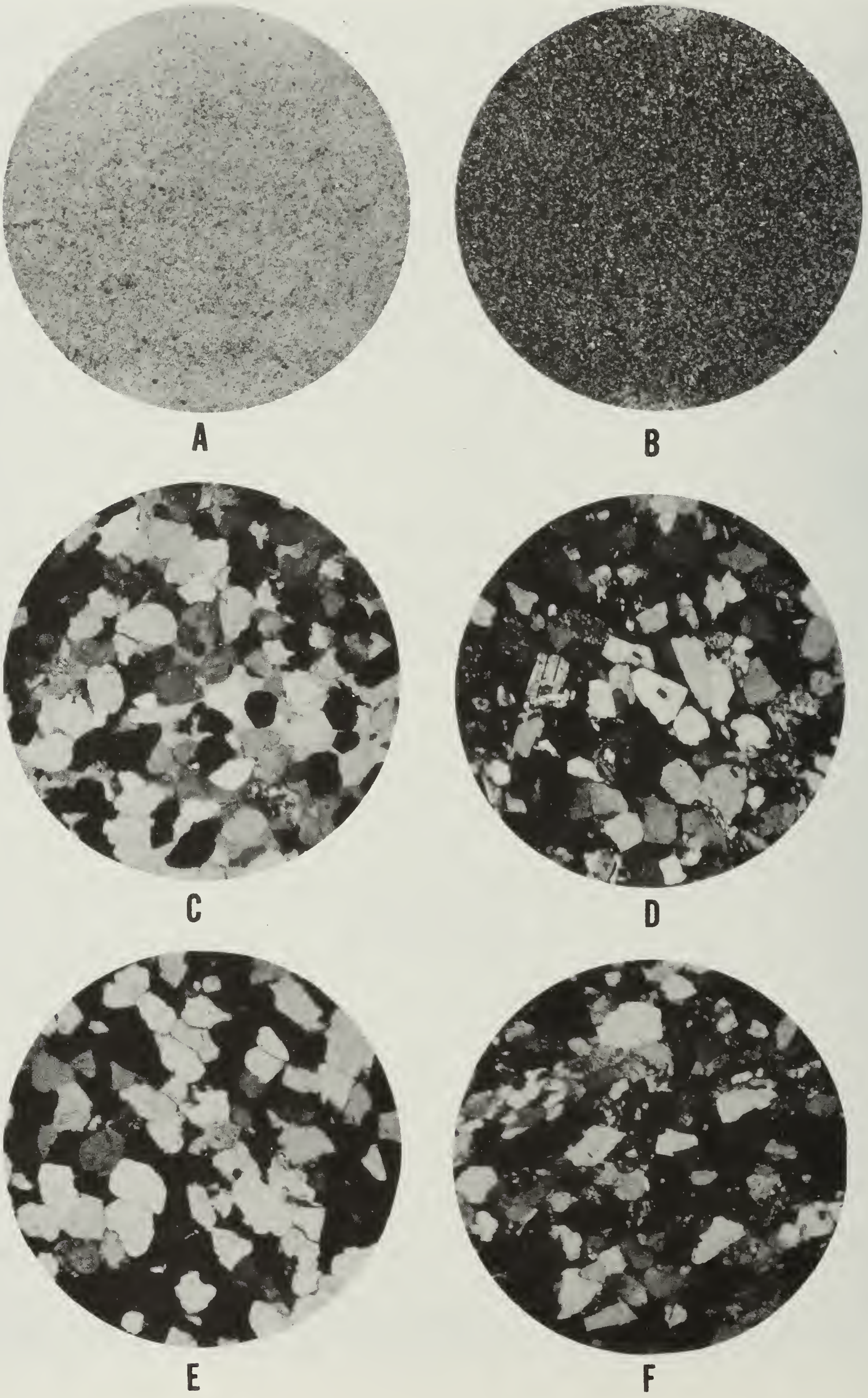
EXPLANATION OF PLATE 5

Two views of a cut-and-fill structure, called a "ripple scour," in a Tradewater sandstone. Note transverse ripples and fill of overlying sand. Exposed in a northeastward flowing creek bed near the road in SE¼ NE¼ NE¼ sec. 4, T. 11 S., R. 2 E., Johnson County, Illinois.

A



B


A
B
C
D
E
F

the more unstable heavy minerals shows a sympathetic variation. All but matrix and mica abundance represent progressively more immature source sediments. The positive correlation of matrix and mica abundance largely reflects sorting at the site of deposition. In contrast, the abundance of the siderite cement is largely an expression of the chemical environment of deposition. Figure 15 clearly indicates the significant contrasts between the Caseyville sandstones, the transition sandstones, and those above the New Burnside coals.

SANDSTONE CLASSIFICATION

Within the past ten years, papers on the classification of sandstone have been numerous (Krynine, 1948; Pettijohn, 1949, 1954; Rodgers, 1950; Dapples et al., 1953; Folk, 1954, 1956; Packham, 1954; Bokman, 1955; Gilbert *in* Williams et al., 1955). This multiplicity of papers results not only from the multiplicity of sandstone components but from the fact that even a single component (such as mica) generally has more than one significance. Certainly classification of a greater number of components is likely to be much more troublesome than classification of a smaller number, and sandstone classification is no exception.

Thus, although several names are available — such as orthoquartzite (Krynine, 1948; Pettijohn, 1949, and 1954; Folk, 1954), quartzose sandstone (Dapples et al., 1953), quartz arenite (Williams, Turner, and Gilbert, 1955) — all clearly mean the same kind of sandstone. We prefer the term orthoquartzite. For the transition group there is somewhat less agreement. The term feldspathic quartzite (Pettijohn, 1954) probably best describes their average composition (table 6). The classification of the sandstones above the Creal Springs is especially troublesome.

The names lithic wacke (Williams, Turner, and Gilbert, 1955, p. 292), graywacke (Dapples et al., 1953, p. 305; Pettijohn, 1954), sublabile graywacke (Packham, 1954, p. 472), and subgraywacke (Folk, 1954 and 1956) all could be applied. When it is remembered that the sandstones above the Creal Springs are sparingly feldspathic, argillaceous, and have abundant shallow-water sedimentary structures, certainly the term graywacke with its turbidity-current implications seems inappropriate. How can the evidence of shallow-water sedimentary structure be reconciled with the high clay matrix of these sandstones? Comparison of clay content from outcrop versus subsurface samples is helpful.

As shown by table 10, the subsurface "subgraywackes" have more carbonate and less matrix than their outcrop equivalents. Hence, even though the outcrop samples were as fresh as possible, vadose-zone weathering produced a great proportion of matrix not related to original sedimentation. Clearly, this should not be considered in the classification of the sand.

Infiltration of clay-sized material into the sandstones after their deposition but before final burial is another possibility. If the extent of the infiltration were significant, it would make misleading any inferences about sedimentation based on matrix content. However, if infiltration were a major factor for the sandstones above the Creal Springs, it apparently was not for the sandstones of the Caseyville group.

A third consideration is based on observation of thin sections. These show that a portion of the material called "matrix" consists of kaolinite aggregates. These aggregates generally appear as veriform books and pseudohexagonal crystals. The individual books of these aggregates average some 4 to 8 microns in

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EXPLANATION OF PLATE 6

Contrasting hand specimen and microscopic appearances of Pennsylvanian orthoquartzites (A, C, and E) and subgraywackes (B, D, and F).

size. (See Glass et al. 1956, for their description in the Caseyville sandstone.) The aggregates may be as large as sand grains. Because of their fragility and size of the aggregates, this kaolinite is considered to be authigenic. Clearly, such matrix elements should not be included in the classification of the sandstone.

Thus clay-silt infiltration related to vadose weathering, infiltration after deposition but prior to final burial, and post-depositional authigenesis all combine to produce more matrix in the present sandstone than was present at the time of sedimentation. Because of their shallow-water sedimentary structures it is very clear that the sandstones should not be called graywackes with any implication of a turbidity-current origin. The name subgraywacke, meaning an argillaceous, sparingly feldspathic sandstone with shallow-water sedimentary structure, seems most appropriate.

The above discussion emphasizes the difficulties that can occur when sandstones are classified in purely petrographic terms, and names with genetic implications are applied. These difficulties can be largely avoided by considering 1) the original detrital elements of the sandstones, and 2) their sedimentary structures. For example, by classifying the argillaceous sandstones into two types, those with and those without typical turbidity–current structures, more natural boundaries with much greater genetic significance can be established. Thus, correlated field and laboratory study of sandstones not only can help to remove some of the arbitrary bounds that exist in most classifications, but also can better link petrographic properties to the physical processes of sediment transport in a depositional basin.

The averages of the three groups of sandstones (table 6) clearly indicate a progressive decrease in both textural and mineralogic maturity from the Caseyville, through the transition group, to the sandstones above the New Burnside coals.

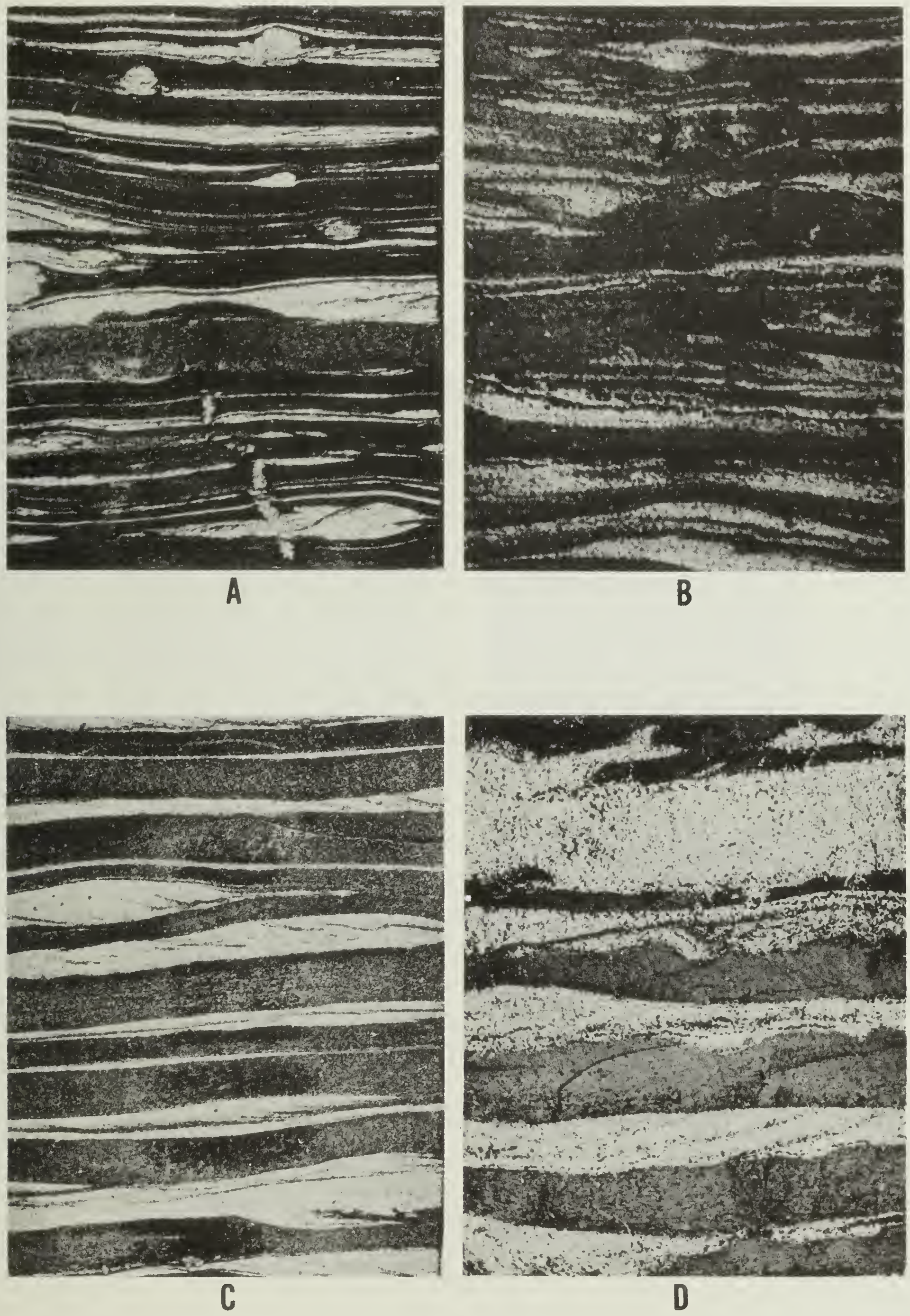
Limestones

From the Shoal Creek limestone to the base of the Creal Springs sandstone, limestones constitute approximately only 2 percent of the total geologic section. They are most numerous from coal No. 5 to the base of the Trivoli cyclothem. With the exception of the Shoal Creek limestone, thicknesses of more than 12 feet for individual limestones in this interval are not common. Both sharp and gradational contacts with the overlying lithologic units are common. In hand specimen, core and outcrop samples range from dense and holocrystalline to soft and argillaceous. The holocrystalline limestones are typically light gray to bluish gray. In the argillaceous samples dark grays dominate. Those limestones that are above the coals in the cyclical sequence are abundantly fossiliferous and contain crinoids, brachiopods, pelecypods, bryozoa, fusulinids, and other forms.

In thin section, the limestones are typically bimodal with the larger mode consisting of both angular and rounded (rare) clastic fossil debris (up to 15 mm. long) that commonly constitutes 10 to 20 percent of the rock but may be as abundant as 50 percent. Even where the coarse mode forms as much as 50 percent of the rock, however, detrital quartz and feldspar grains are generally rare and are generally less than .25 mm. long. Marginal replacement of both quartz and feldspar by matrix carbonate is common. In the 12 thin sections studied there were

EXPLANATION OF PLATE 7

Comparison of Pennsylvanian siltstone-shale interlaminations (A and C) and modern tidal flat interlaminations (B and D) from the Wadden Sea, Netherlands. B is a photograph of a vertical section of recent Wadden Sea mud flat. D is a photograph of a vertical section of recent Wadden Sea channel floor deposit. Approximately natural scale. (Photographs B and D from Van Straaten, Plate 1, 1954.)


A
B
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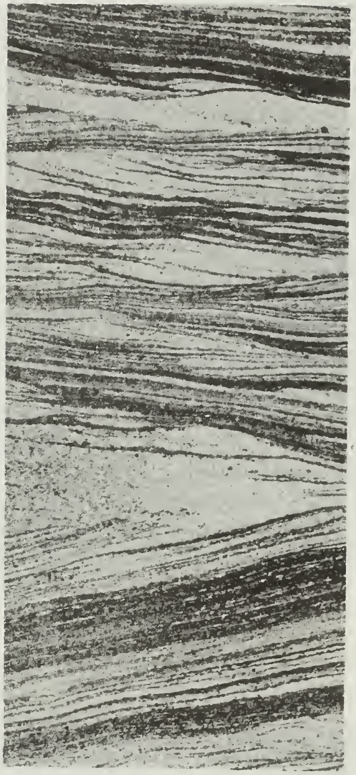
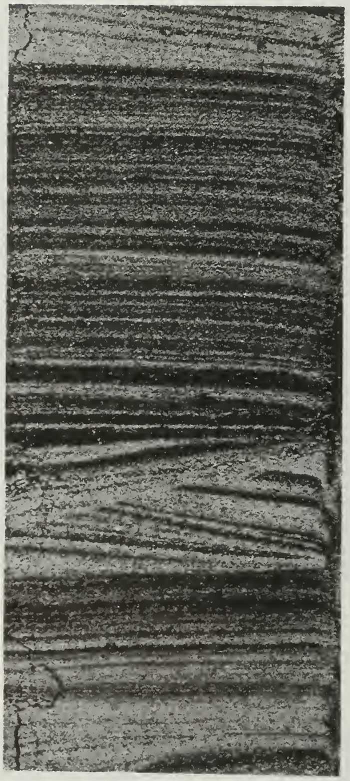
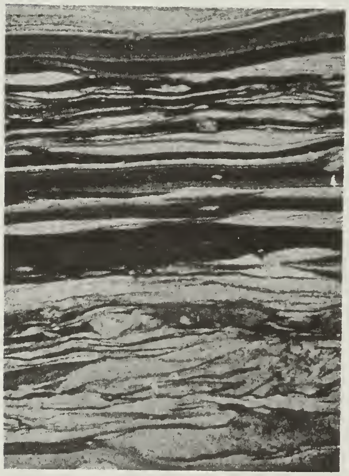


A



B



C

D

no authigenic overgrowths on detrital quartz and feldspar. The matrix of clastic fossil debris is typically a fine-grained (.01 to .03 mm.) mosaic of anhedral and subhedral carbonate and clay. The clay is in minor amounts but is disseminated in and between the small carbonate grains of the matrix, giving it a dirty appearance.

In contrast to the matrix, coarser, clear carbonate of granoblastic texture is most abundant as the internal filling of fossil shells. Where the larger clastic elements constitute only 10 to 20 percent of the rock, the fine-grained, dirty matrix is predominant; where the larger clastic elements form a larger percentage of the rock, clean, coarse (individual crystals up to .25 mm.), granoblastic carbonate is more abundant as a cement. Collophane is present in most slides as a replacement of skeletal carbonate. A few grains of "glauconite" were observed. Euhedral and anhedral pyrite is a persistent but very minor authigenic accessory mineral.

Semiquantitative estimates of carbonate mineralogy based on x-ray diffraction patterns indicate the presence of appreciable amounts of dolomite in "limestones" below the Trivoli. Differential thermal analysis identified the dolomite as ferroan dolomite in all cases. The ferroan dolomite content is highly variable, ranging from almost pure ferroan dolomite to almost pure calcite. Mixtures are more typical, however. Siderite occurs in minor amounts in a few samples. In a more comprehensive study, Siever and Glass (1957) found a similar carbonate mineralogy.

CLAY MINERALOGY

The less than 2-micron fraction was obtained for all samples of shales, sandstones, and insoluble residues of limestones by decantation, using Stokes' law to compute settling times. The limestones were first treated with dilute acetic acid to remove carbonate. Acetic acid treatment, in contrast to hydrochloric acid treatment, does not appreciably alter the clay mineral assemblage.

Oriented aggregates on glass slides were used for x-ray diffraction analyses. X-ray patterns were obtained both before and after ethylene glycol treatment. The abundance of kaolinite, mica (illite), chloritic clay minerals, and mixed-lattice materials were determined with a precision of 1 part in 20 when possible. The estimates are based on the relative intensities of the basal (001) sequences of the several clay mineral groups. The presence of feldspar, calcite, siderite, and gypsum also was noted. Two typical x-ray spectrometer tracings, one of the clay minerals from a sandstone and the other from a shale, are shown in figure 16.

Quantitative results of the study are given in table 8. Plots of clay mineral composition versus stratigraphic position are shown in figure 3. Table 9 shows the order of abundance of clay minerals for all the Pennsylvanian shales of this study, and indicates a mica-chlorite association with lesser amounts of kaolinite and mixed-lattice materials.

POST-DEPOSITIONAL DIAGENESIS

Before a source area can be assessed or an environment interpreted, it is necessary to evaluate at least the major changes induced by post-depositional diagenesis. The contrast between outcrop and subsurface samples has strong bearing on the post-depositional diagenetic changes in sandstones and shales.

The average modal and detrital compositions of the Caseyville orthoquartzites of southern Illinois (Siever and Potter, 1956) and the subgraywacke sandstones above the New Burnside coal are listed in

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EXPLANATION OF PLATE 8

Comparison of Pennsylvanian siltstone-shale interlaminations (A and C) and modern Texas Gulf Coast interlaminations (B and D). Photograph B shows Gulf Coast laminated and cross-laminated very fine sands and silts from delta margin (fringe). Photograph D is of Gulf Coast deltaic margin (fringe) laminated and cross-laminated very fine sands and silt-clays from shallow water (less than 10 feet) near a distributary. Note load cast. Approximately natural scale.

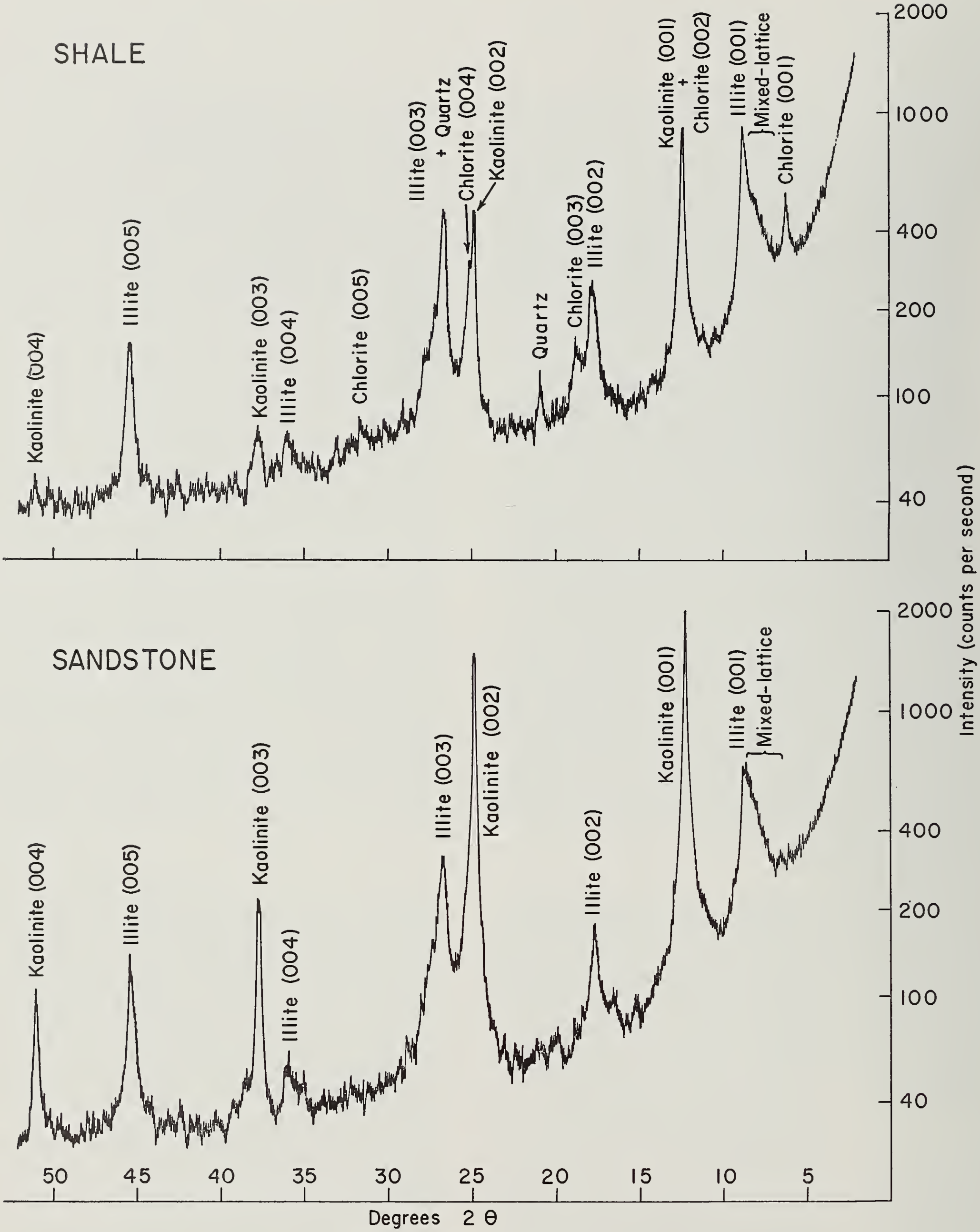

Fig. 16. — X-ray spectrometer patterns (Cu radiation) of the clay fraction from a subgraywacke sandstone and an associated shale showing the clay-mineral reflections of the various 001 orders. Labeling of the weak and diffuse mixed-layer reflections in the 16 to 18 and 25 to 27 degree ranges were omitted for simplicity.

Table 8.—Pennsylvanian Clay Mineral Composition
(parts in ten)

Sample number	Kaolinite	Mica	Mixed lattice	Chlorite	Quartz	Feldspar	Calcite	Siderite
			A. Shales—subgraywacke facies					
585*	2.5	3.5	1.5	2.5	C	P		
589*	3.0	2.0	5.0	?				
582	1.5	5.0	1.5	2.0	P	P		
583	0.5	3.0	5.0	1.5			C	
584	?	3.0	5.5	1.5	P		C	
500	1.5	5.0	1.0	2.5	P	P		
501	2.0	4.5	1.5	2.0	P			
502	1.5	5.0	1.0	2.5	C	P		
503	1.0	5.0	1.5	2.5	P	P		
504	1.5	5.0	1.0	2.5	P			
505	1.0	5.0	1.5	2.5	C	P		
506	1.0	4.5	1.5	3.0	P	P		
507	1.0	5.5	1.5	2.0	P	P	C	?
509	1.5	4.0	2.0	2.5	C	P		
508	1.5	5.0	1.0	2.5	P	P		
510	2.0	2.5	3.0	2.5	P	P		
511	1.5	4.5	1.5	2.5	C	P	P	P
512	2.0	4.0	1.5	2.5	P	P	P	?
513	2.0	4.5	1.0	2.5	P	P		
514	2.0	4.5	1.0	2.5	P		P	P
515	2.0	3.5	2.0	2.5				
516	2.5	4.0	1.5	2.0				
517	0.5	6.5	1.0	2.0				
518	1.0	5.5	1.0	2.5	P			P
519	1.5	4.5	1.0	3.0	P			
520	1.0	5.5	1.0	2.5	P	P		P
521	1.0	5.5	1.0	2.5	P	P		
522	2.0	5.0	0.5	2.5	P	P		
523	2.0	4.5	1.0	2.5	C	P	P	
524	1.5	5.0	0.5	3.0	P	P	P	?
525*	3.0	4.0	3.0	?	C		P	
526	1.5	4.0	2.0	2.5	P		P	P
527	1.5	4.5	2.0	2.0	C	P		
528	2.5	5.0	1.5	1.0				
529	2.5	5.0	1.5	1.0	P	P		
530	2.0	4.0	1.5	2.5	C	P	?	
531	2.0	4.0	1.5	2.5	P	P	P	
532	1.0		9.0		P		P	
533	2.0	4.5	0.5	3.0	P	P	P	
534	1.5	5.0	1.0	2.5	C			
535	1.5	4.5	1.5	2.5	P			
536	1.0	5.0	1.5	2.5	C	P	C	
537	2.0	4.0	4.0		P			
539	2.0	4.5	1.0	2.5	P		P	
540	2.0	3.0	5.0		P	P		
541	2.5	2.5	2.0	3.0	P	P		
542	2.0	3.5	1.5	3.0	C	P	P	
543	2.0	5.0	0.5	2.5	C	P		
545	2.0	5.0	0.5	2.5	P	P	P	

* Outcrop sample.
P, present; C, common; and A, abundant.

Table 8.—continued

Sample number	Kaolinite	Mica	Mixed lattice	Chlorite	Quartz	Feldspar	Calcite	Siderite
546	2.0	5.0	1.0	2.0	P		P	
547	2.0	4.5	1.0	2.5	P			
548*	5.0	3.0	2.0					
586*	2.0	5.0	1.0	2.0	P			
549*	4.0	5.5	0.5	0.0				
550*	1.0	6.0	1.5	1.5	C			
551*	1.0	6.0	1.0	2.0	P			
595*	5.0	2.0	3.0					
552*	5.0	3.0	2.0		P			
588*	1.5	4.5	2.0	2.0	P			
593*	2.0	4.0	3.0	1.0				
594*	1.5	5.0	2.0	1.5	C			
592*	1.5	5.0	2.0	1.5	C			
A. Shales—transition group								
553	1.5	4.5	1.0	3.0	P		P	
554	2.0	4.0	2.0	2.0	P			
555	1.0	5.5	1.5	2.0	P			
556	1.0	6.0	1.5	1.5				
557	2.5	4.0	1.0	2.5	P			
558	1.5	4.5	1.5	2.5	P			
559	1.5	5.0	1.5	2.0	P			
560	3.0	3.0	1.0	3.0	P	P	P	
561	2.5	3.0	1.5	3.0	P	P	C	
562	2.0	4.5	1.5	2.0	P		P	
563	2.5	4.5	1.5	1.5	P		C	
A. Shales—orthoquartzite facies								
578	1.0	5.5	1.5	2.0	P			
579	1.0	5.5	1.5	2.0	P			
564	1.0	5.0	2.0	2.0			P	
580	1.0	5.5	2.0	1.5				
598*	1.0	6.5	1.0	1.5	P			C
599*	1.5	7.5	1.0				P	P
590*	1.5	7.0	1.0	0.5	C			
591*	0.5	7.0	1.0	1.5	P			
565	1.0	6.0	1.5	1.5	P	P	P	
581	1.0	6.0	2.0	1.0				
566	1.0	6.5	1.0	1.5	P		C	
567	1.5	6.0	1.0	1.5	C			
568	1.0	6.0	1.5	1.5	P			
569	1.0	6.0	1.5	1.5	P		C	
570	1.0	6.0	1.5	1.5	P		P	
571	1.0	6.0	1.5	1.5	P			
572	1.0	6.5	1.5	1.0	P			
573	1.5	7.0	1.5		P			
597*	2.5	5.0	2.5		?			Fe hydrate
596	1.5	5.5	1.5	1.5				
600*	3.0	3.0	3.0	1.0	?			Fe hydrate
601*	3.5	3.5	3.0		P		P	
602*	1.0	1.0	8.0		P			
574	1.5	5.5	1.0	2.0	P			
575	1.5	5.0	1.0	2.5				
576	1.5	5.0	1.5	2.0		P		
577	2.0	3.5	1.5	3.0	C	P		

* Outcrop sample.
P, present; C, common; and A, abundant.

TABLE 8.—concluded

Sample number	Kaolinite	Mica	Mixed lattice	Chlorite	Quartz	Feldspar	Calcite	Siderite
B. Sandstones—subgraywacke facies								
330*	4.0	3.0	1.0	2.0	P	P		
301*	4.5	3.5	0.0	2.0	P	P	C	
300	1.5	4.0	2.5	2.0	P		P	
10	4.0	3.0	1.0	2.0	P	P		P
290	4.0	3.5	1.0	1.5	P	P	P	
11	5.0	3.0		2.0	P	P		
328*	5.0	3.0		2.0	P	P		
329	5.0	3.0		2.0	C	P	P	P
13	3.0	5.0	0.5	2.0	C	P	P	
291*	5.0	2.5		2.5	P	P		
379*	6.0	2.0		2.0	P	P		
14	3.0	5.0	1.0	2.0	C	P	P	
292*	5.0	3.0		2.0	P	P		
293*	3.0	5.0		2.0	C	P	P	P
16	3.0	5.0	0.5	2.0	P	C		
294	6.0	1.5	2.5		P	P		
303*	4.0	2.5	1.5	2.0	C	P		
299	3.0	5.0	0.5	2.0	P	P	P	
B. Sandstones—transition group								
18	4.5	3.0	0.5	2.0	C	P	P	
39	4.0	4.0		2.0	C	P	P	
20	3.5	2.5	2.0	2.0	A	P		P
38	3.0	2.0	2.0	3.0	A	P		P
22	4.0	3.0	1.5	1.5	C	P		P
24	5.0	2.0	3.0		C			P
25	3.5	4.5	1.5	0.5	C	P		P
B. Sandstones—orthoquartzite facies								
295	2.5	3.5	1.0	3.0	C			P
40	4.0	3.0	3.0		A		C	P
26	3.0	4.0	3.0		C			C
41	4.5	2.5	3.0		A			C
42	2.0	4.0	3.0	1.0	C			C
27	4.5	4.0	1.5		C	P		P
28	3.5	2.5	4.0		C			P
C. Limestones—subgraywacke facies								
298		3.0	5.0	2.0	P	P		P
316	1.5	6.0	0.5	2.0	C	P		P(Fe_2O_3)
314	1.5	5.0	0.5	3.0	P	P		
318	1.5	5.0	1.0	2.5	C	P		
315	3.0	2.5	2.5	2.0				
381	1.0	4.0	3.0	2.0	P	P	P	P
604	1.0	4.0	2.5	2.5	P	P		
605	1.0	5.0	4.0		P			
312	1.0	5.0	4.0		C			P(Fe_2O_3)

* Outcrop sample.
P, present; C, common; and A, abundant.

Table 9.—Ranking of Clay Mineral Composition in Pennsylvanian Shales
(in percent)

	First in abundance	Second in abundance	Third in abundance	Fourth in abundance
Kaolinite	5.3	17.0	50.2	29.9
Mica	86.7	5.9	1.7	0.0
Mixed-lattice	7.2	19.2	37.6	48.8
Chlorite	0.8	57.9	10.5	21.3

table 10. The table shows the striking deficiency of carbonate in the outcrops of both petrographic types. Obviously then, even though an effort was made to obtain the least weathered samples, most of the outcrops of this area are well within the zone in which carbonates are leached by meteoric waters. By recomputing the composition of the subsurface samples on a carbonate-free basis, their detrital composition can be compared to that of the outcrop samples. As shown by table 10, there is little difference except for clay matrix in detrital composition between outcrop and subsurface for either petrographic type. For sandstones the effect of outcrop alteration on the major detrital components studied in this section is thus negligible.

Because there is an upward decrease in maturity of the light mineral detritals, one might anticipate a corresponding pattern for the heavy minerals. However, the heavy minerals of the subgraywackes differ only slightly from those of the orthoquartzites. Even though apatite and garnet appear and biotite and chlorite become more abundant, zircon, tourmaline, and rutile remain the dominant heavy minerals of the subgraywackes. Apatite, garnet, and biotite approach rutile, zircon, and tourmaline in stability (Pettijohn, 1941, p. 619). Certainly it would seem reasonable to expect the appearance, even if only in quantities of less than one percent, of some minerals commonly associated with quartzofeldspathic terrains, such as epidote, hornblende, monazite, kyanite, staurolite, and sillimanite. Why are these minerals absent in sandstones that have had such a short abrasion history? It is unlikely that they could have been eliminated by mechanical abrasion during transport. For that portion of the subgraywackes that had had some previous abrasion history, surficial weathering or intrastratal solution would have eliminated these less stable species. Post-Pennsylvanian intrastratal solution is still another possibility. Because clay minerals as a group probably are more susceptible to quasireversible processes (Grim and Bradley, 1955, p. 471-474) during weathering, transport, and burial than are heavy minerals, the possibility of appreciable intrastratal solution of the heavy minerals raises the possibility of a parallel post-depositional alteration of the clay minerals of the sandstones.

To assess such possible alteration, it was necessary to evaluate the role of contrasting source area contributions (inheritance), contrasting permeabilities (shales versus sandstones), and contrasting exposure to meteoric waters (outcrops versus cores). This was done by sampling both the shales and sandstones in outcrops and cores from both petrographic facies. The eight pairs of interpenetrating samples shown in table 11 resulted from such a sampling plan.

Table 11 shows that in cores there is a striking difference between the clay mineral composition of orthoquartzitic sandstones and their associated shales. In the cores, the orthoquartzitic sandstones have more kaolinite, less mica and mixed-lattice materials, and less chlorite than their associated shales. When the subgraywackes are considered, a like contrast is found. Subgraywacke core sandstones definitely have more kaolinite and less mica than their associated core shales, whereas contrasts in mixed-lattice materials and chlorite are less pronounced.

Because many of the sandstones and shales were intimately interbedded, it is

Table 10.—Average Composition of Subgraywacke and Orthoquartzite Outcrop and Core Samples

	Quartz	Clay	Carbonate	Feldspar	Mica	Rock fragments and chert	Misc.	No. of samples
		Subgraywackes						
		Modal Composition						
Outcrop	63.4	22.4	0.1	5.1	3.9	2.9	2.2	8
Subsurface	53.5	15.8	18.7	3.2	3.5	3.1	2.2	10
		Detrital Components						
Outcrop	63.4	22.4	—	5.1	3.9	2.9	2.2	8
Subsurface	65.8	19.4	—	4.0	4.3	3.8	2.7	10
		Orthoquartzites						
		Modal Composition						
Outcrop[a]	93.4	5.2[b]	0.0	0.1	—[c]	1.3	—[c]	11
Subsurface	83.5	4.3	9.9	0.2	—[c]	2.1	—[c]	7
		Detrital Components						
Outcrop[a]	93.4	5.2[b]	—	0.1	—[c]	1.3	—[c]	11
Subsurface[a]	93.7	4.8	—	0.2	—[c]	2.4	—[c]	7

[a] Data from Siever and Potter, 1956, table 24, p. 321-322.
[b] Mica included with clay.
[c] Not differentiated.

TABLE 11.—AVERAGE CLAY MINERAL CONTRASTS BETWEEN TWO LITHOLOGIES AND PETROGRAPHIC FACIES IN OUTCROPS AND CORES
(parts in ten)

	Outcrops					Cores				
	Kaolinite	Mica	Mixed lattice	Chlorite	No. of samples	Kaolinite	Mica	Mixed lattice	Chlorite	No. of samples
Orthoquartzitic facies										
Shales	1.8	4.6	2.4	1.2	11	1.1	6.1	1.4	1.4	17
Sandstones	5.0	2.5	1.5	1.0	18	3.4	3.4	2.6	0.6	7
Subgraywacke facies										
Shales	1.7	4.8	1.5	2.0	8	1.5	4.6	1.5	2.4	38
Sandstones	4.7	2.9	0.6	1.8	9	3.5	3.8	0.8	1.9	9

unreasonable to ascribe this contrast to either contrasting inheritance or local depositional environment. Therefore this contrast is believed to be of post-depositional origin. Petrographic evidence demonstrates the presence of authigenic kaolinite aggregates that may be as large as sand grains. Clearly, kaolinite aggregates of such size are not detrital.

In both orthoquartzitic and subgraywacke sandstones, therefore, post-depositional alteration in the core has produced significant change (more kaolinite and less mica) in the clay fraction of the sandstones. Exposures of both sandstone types to meteoric waters has notably heightened this contrast. The outcrop samples of both subgraywacke and orthoquartzitic sandstones are appreciably richer in kaolinite and poorer in mica than their core equivalents (table 11).

In comparison to the sandstones, the shales show less marked contrasts between core and outcrop. For the shales of the subgraywacke facies, outcrop and core compositions are nearly identical. In the orthoquartzite facies, shale outcrops are somewhat richer in kaolinite and mixed-lattice materials and poorer in mica than their core equivalents. Thus even low permeability sediments like shales may show differences in composition between outcrop and core.

The above interpretation thus lends additional support to the previous conclusion of Glass et al. (1956) that the contrasting permeabilities of ancient sediments can strongly influence clay mineral composition. The foregoing discussion shows that the contrasting permeabilities of ancient sediments can affect clay mineral composition in the subsurface as well as in outcrop. This implies that formation of clay minerals need not necessarily cease upon burial of a sediment but can proceed more or less continuously during later geologic history. We have indicated, too, that exposure to meteoric waters (in outcrop) can accelerate clay mineral change. The post-depositional history of the clay minerals thus can be a significant factor in clay mineral composition, especially for the more permeable sediments. Thus the best estimates of clay mineral composition at the time of deposition are obtained from shales, and preferably from core shales.

PROVENANCE

By provenance we mean the location and composition of the source area and its tectonic and climatic condition.

Because the Pennsylvanian sediments of the Eastern Interior coal basin are far removed from such possible major source areas as the Canadian shield or inferred Paleozoic highlands east of the present Appalachian basin (fig. 1), provenance inferences obtained from a "vertical-point" profile in the Eastern Interior coal basin will emphasize source-area composition and tectonics rather than location. However, even though the cross-bedding in the Williamson County area does not permit us to distinguish between the shield and the Paleozoic highlands as possible major source areas, it does have strong bearing on the probable transport pattern in the basin.

Probable Transport Pattern

Cross-bedding orientation in the basal Caseyville, Mansfield, and Babylon sandstones of the Eastern Interior coal basin, and in their stratigraphic equivalents, the Lee, Sharon, and Parma sandstones of the Appalachian and Michigan basins, has been studied by Potter and Siever (1956, part I). Their study shows that, excluding the western shelf area of the Eastern Interior coal basin (fig. 2-B), the flow pattern of these basal Pennsylvanian sandstones was to the southwest (fig. 17). On the western shelf area, cross-bedded outcrops were few but indicated a southeastward flow pattern. The contrasting flow patterns have companion contrasts in detrital mineralogy (Siever and Potter, 1956, part II). The Babylon sandstones of the western shelf area of the Eastern Interior coal basin have well rounded grains, negligible feldspar, metamorphic quartz in low abundance, and no metamorphic quartz pebbles. The sandstones with contrasting flow pattern have less well rounded grains, minor feldspar, metamorphic quartz in greater abundance, and widespread metamorphic quartz pebbles. Figure 17 depicts the contrasting basal Pennsylvanian flow patterns and mineral associations in the Eastern Interior coal basin as well as the cross-bedding direction of the post-Caseyville sandstones in the Williamson County area.

The above data show that the cross-bedding direction of the post-Caseyville sandstones of the Williamson County area is essentially similar to that of the Caseyville and Mansfield sandstones of the Eastern Interior coal basin. The similarity of flow pattern in vertical profile to that of the Caseyville-Mansfield, a relatively thin basal unit studied over a wide area, strongly suggests that most of the post-Caseyville sediments of the Eastern Interior coal basin had a southwestward transport pattern.

It would appear, therefore, that the initial southwestward tilt of the craton (orientation of subaerial channels of the Mississippian-Pennsylvanian unconformity and basal cross-bedding) persisted throughout much of the post-Caseyville-Mansfield history of the basin, even though the rate of basin subsidence subsequently became much greater. This suggests that throughout much of its history, sediments entered the Eastern Interior coal basin from the east, northeast, and north, and that the dominant transport pattern was to the south-southwest toward the now buried thick belt of Pennsylvanian sediments that connect, across the Mesozoic-Mississippi embayment, the Black Warrior basin in Alabama with Ouchita trough in Oklahoma (Morgan, 1952).

The above interpretation harmonizes with stratigraphic evidence that indicates the Eastern Interior coal basin was open-ended along its present southern structural border. It also lends additional support to the conclusion of Potter and

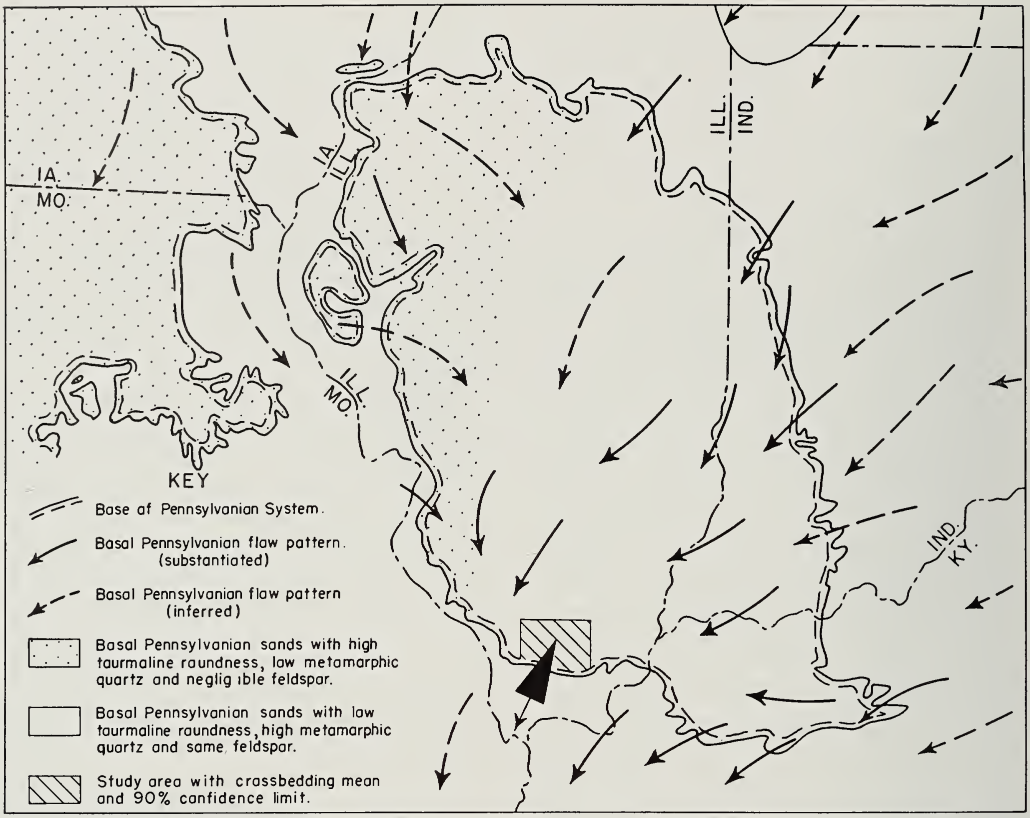

Fig. 17. — Post-Caseyville cross-bedding mean and 90 percent confidence wedge of study area (ruled) superimposed on basal Pennsylvanian flow pattern and mineral associations (adapted from Potter and Siever, 1956, p. 242, fig. 7).

Siever (1956, part III) that in clastic sedimentation on cratons, in intracratonic basins, and in the pre-orogenic phases of geosynclines, preferred directions of sediment transport persist throughout many feet of deposition, and are the rule rather than the exception.

Composition of the Source Area

Because the transition sandstones are a hybrid of the older orthoquartzites and younger subgraywackes, prime emphasis is given here to the source-area composition of the orthoquartzites and subgraywackes. Inferences are based primarily on the light and heavy minerals of the sandstones and, to a minor degree, on clay mineralogy and the quartz pebble conglomerates. Table 12 summarizes for both rock types the significant source-area properties, their possible transport and post-depositional modification, their abundance, and their source-area inference.

For the orthoquartzites, the small amounts of feldspar, biotite, and chlorite, and rock fragments all indicate a source area composed dominantly of pre-existing sediments. The almost complete dominance of zircon, tourmaline, and rutile substantiates this conclusion. Because about a third of the tourmalines are well rounded, it is inferred that a significant portion of these sediments had a long history of abrasion. Because quartz pebbles are very durable (Plumley, 1948, p. 570-574), it could be argued that less mechanically stable feldspathic pebbles and cobbles were present in the source area but had been eliminated in transport to the Eastern Interior coal basin. If this were so, their abrasion would have produced more feldspar in the sand fraction. The nearly complete absence of feldspar and other associated less stable minerals indicates that the quartz pebble conglomerates also were derived from preexisting sediments. All the available petrographic evidence thus points to a sedimentary source in which crystalline rocks were insignificant and in which approximately a third of the sediments had abrasion histories sufficient to produce round tourmaline grains. The dominance of both angular and prismatic tourmaline grains indicates, however, that most of these sediments were still only a few cycles removed from parent crystalline rocks.

Because of the subgraywackes' greater mineralogical immaturity, it might be deduced that transport abrasion resulting from 500 to 1,000 miles travel from possible source areas produced significant changes in the less mechanically stable detrital minerals. Studies of modern fluvial sediments (Plumley, 1948, p. 573) indicate that elimination of feldspar by transport abrasion can be appreciable in streams with high gradients. Conversely, in streams with low gradients, such as the Mississippi from Cairo, Illinois, to the Gulf, loss of feldspar is negligible (Russell, 1937). As shown by the scarcity of oriented load casts, the depositional slope of the coal basin was slight. It is likely that low gradients persisted far toward the source region. However, in and near the distal portions of the source region, higher gradients associated with a mountainous terrain seem likely, and the possibility of appreciable (50 to 80 percent) feldspar loss should be considered.

The positive correlation between sand- and clay-fraction feldspar (table 8 and fig. 15) in both the subgraywackes and orthoquartzites is consistent with such an interpretation because it could, but need not necessarily, have resulted from attrition of sand-fraction feldspar. Unstable fragments of siltstones, argillite, and low-grade micaceous metamorphic rocks similarly would be significantly eliminated by transport. In contrast, both micaceous minerals and heavy minerals appear to be relatively little affected by transport. As we have already seen, tourmaline roundness is largely the result of abrasion prior to the Pennsylvanian cycle.

Judging from the subgraywackes' greater mineralogical immaturity, possible post-depositional modification (intrastratal solution) could have been appreciable for some of the detrital elements. In contrast, the abundance of biotite and chlorite, feldspar, chert, and tourmaline roundness have been largely unaffected by intrastratal solution.

The source area of the subgraywackes differs from that of the orthoquartzites in that feldspathic rocks of either igneous and/or metamorphic origin were important, some metamorphic rocks (garnet) were present, and sediments with a long abrasion history were negligible. A large portion of the clastics probably had not had more than one previous cycle of transport. The absence of quartz pebbles is so complete as to suggest either up-dip overlapping by progressive Pennsylvanian sedimentation, or drainage diversion in the source-area hinterland. The former seems the more likely. Although the subgraywackes were deposited with a much greater proportion of sediments of *known marine* origin than were the orthoquartzites, the greater proportion of chloritic clay minerals in the subgraywacke shales could, but need not necessarily, reflect a more immature source-area contribution.

SANDSTONE MATURITY

Within recent years the concept of a mature sandstone as being one composed of mineralogically stable, well sorted, and well rounded grains has been emphasized (Plumley, 1948, p. 571-574); Folk, 1951; Pettijohn, 1954, p. 361-362; Gilbert *in* Williams et al., 1955, p. 289-297; and others). How far along the path to the ultimate in maturity are these Pennsylvanian sandstones? The St. Peter sandstones

Table 12.—Petrographic Properties and Composition of Source Area

Property	Modification by		Orthoquartzites		Subgraywackes	
	Transport	Post-depositional diagenesis	Average abundance	Inference	Average abundance	Inference
Quartz pebbles	Mechanically durable; present roundness probably acquired in first 100 miles of transport	None	Prominent in outcrop but generally less than 1 percent in size analyses	Probably conglomerates of pre-existing sediments; most ultimately derived from quartz veins, some from quartzitic sandstones	None	Absence so complete as not to suggest dilution in source area; hence, absence due to overlap or drainage diversion in hinterland
Feldspar	Could be significant if high gradients	Negligible	1 percent or less	Mostly mature pre-existing sediments	5.7 percent	Crystalline rocks significant (5 to 20 percent?) in source area
Biotite and chlorite	Possibly some elimination by transport	Alteration of biotite to chlorite probable	Negligible in thin section; 13 percent in heavy mineral slides	Mostly mature pre-existing sediments	Present in thin section; 31 percent in heavy mineral slides	Coarse-grained feldspathic igneous and/or metamorphic rocks significant supplement to sediments
Sedimentary rock fragments (non quartzose)	Elimination by transport appreciable	Negligible	Negligible in sand fraction	Mature pre-existing sediments	4.1 percent	Some far-derived, but probably most of local origin
Chert	Elimination by transport negligible	Negligible	Approximately 1 percent	Pre-existing sediments that included, at some stage, carbonates	Negligible	Chert-bearing carbonates and bedded cherts, probably very rare in source area
Kinds of heavy minerals	Elimination by transport negligible	Probably extensive	Zircon, tourmaline and rutile generally constitute over 95 percent	Mature pre-existing sediments	Zircon, tourmaline and rutile still dominant but garnet and apatite also present	Garnet and apatite along with *angular* and *prismatic* tourmaline suggest appreciable post-depositional alteration from an immature suite. Hence crystalline rocks significant supplement to sediments
Tourmaline roundness	Little	None	32 percent of tourmaline rounded	Approximately ⅓ of source rocks had a long history of abrasion	2 percent tourmaline rounded	Rocks with a long abrasion history were negligible. Crystalline rocks and "first" and "second" cycle sediments dominant

Clay minerals	Degradations induced by source area weathering and transport tend to be recovered in marine basins. Possibly some segregation with pH change upon entering marine basin	Appreciable for the more permeable sediments in both cores and outcrop	In shales from subsurface, mica greater than 50 percent and kaolinite, mixed-lattice and chlorite 10 to 15 percent	Difficult to assess because of changes induced by transport and depositional environment but probably closely reflects source-area composition	In subsurface shales mica 45 percent, chlorite 25 percent, and kaolinite and mixed-lattice approximately 15 percent	Difficult to assess because of changes induced by transport and depositional environment, but more chlorite could, but need not necessarily, reflect a more immature source area

of the Upper Mississippi Valley region provide a useful comparison.

Mineralogically, the detrital elements of the St. Peter sandstone in Illinois, Iowa, and Missouri consist almost entirely of quartz, zircon, tourmaline, and rutile (Dake, 1921, p. 136-148; Thiel, 1935, p. 589-599). Feldspar and rock fragments are negligible. The St. Peter is thus generally somewhat more mature mineralogically than the Caseyville and much more mature than the Pennsylvanian subgraywackes. The comparative sorting of these sandstones is shown in table 7.

Evaluation of these data with the test of all contrasts (Scheffé, 1953; Horberg and Potter, 1955, p. 21-22) shows the sorting of the subgraywacke differs at the 5 percent level from that of both the St. Peter and Caseyville sandstones and that the St. Peter and Caseyville are comparably sorted. In the size range 0.062 to 0.5 mm. the tourmaline roundness of ten samples of the St. Peter sandstones from the Upper Mississippi Valley region was compared to that of the Pennsylvanian sandstones. Figure 18 shows the resultant contrasts and indicates that the St. Peter sandstone is much better rounded than the Pennsylvanian sandstones.

Thus, even though the Caseyville sandstones are as well sorted as the St. Peter and approach them mineralogically, the St. Peter sandstones are clearly the most mature. This comparison lends support to the view of Plumley (1948, p. 570-574) and Folk (1951) that sediment sorting proceeds at a much greater rate than elimination of unstable minerals by transport abrasion and that both proceed more rapidly than the rounding of sand grains. This viewpoint implies that even the comparatively mature Caseyville orthoquartzites would require much more transport to equal the St. Peter sandstone.

The matrix of the subgraywacke sandstones suggests, however, that there are at least minor exceptions to the three sequential steps — sorting, elimination of unstable minerals, and roundness. Both sedimentary structures and thin-sections

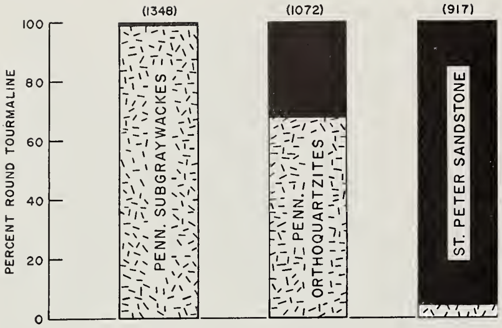

Fig. 18. — Black shows percentage of round tourmaline grains (0.062 to 0.5 mm.) of the Pennsylvanian subgraywackes and orthoquartzites and the Ordovician St. Peter sandstone. Number of grains counted shown in parentheses.

indicate that at least some of the matrix clay of the subgraywacke sandstones is unrelated to original deposition. More generally, a well sorted, and even a well rounded, sand fraction can be associated with appreciable clay matrix. Hence, depending on local sorting, there can be occasional textural "regressions" in the over-all maturity sequence.

ENVIRONMENT OF DEPOSITION

By depositional environment we mean a site of deposition such as an offshore bar, an alluvial fan, a tidal flat, or similar feature where the physical, chemical, and geologic processes associated with deposition have produced distinctive sedimentary attributes prior to final burial of the sediments. A modern depositional environment is thus simply a geographic place where physical processes presumably produce distinctive sedimentary attributes. The recognition of these modern environments in ancient sediments seems to involve two distinct steps.

The first step is an integration of the sedimentary attributes in the ancient sediments to obtain a qualitative (and less commonly quantitative) picture of the major physical, chemical, and biological processes that affected the sediments at the site of deposition. The second step is the identification of an equivalent modern place (tidal flat, shallow marine shelf, or similar feature) where comparable attributes exist today.

Success appears to depend on the kind and size of geographic place. That is, the attributes of the modern sediments of a large delta or a shallow marine shelf are likely to be more easily recognized in ancient sediments than are the attributes of the geographic subdivisions within them. The second step is the difficult one because, depending upon the kind and size of the geographic unit, these physical, chemical, and biological processes are not always uniquely tied to a single modern geographic place. This is largely because the sedimentary processes in many modern geographic environments differ more in degree than in kind. Thus, in many instances, the worker in ancient sediments may be able to make only a qualitative reconstruction of the physical processes and to associate these processes with large equivalents such as shelves, basins, and troughs, rather than with small-scale modern equivalents.

Environment

The major environmental contrasts in the Pennsylvanian sediments of the Williamson County area are those above and below the New Burnside coals (table 1).

Below the New Burnside coals, sandstones are dominant, marine fossils are rare, limestones have not been found, and coal beds are thin and of limited lateral persistence. Rapid sedimentation rates as well as rapidly shifting loci of sand deposition are inferred. As demonstrated by cross-bedding, transport direction of the sandstones was to the southwest. Initially orthoquartzites in the Caseyville, the sands became more argillaceous and feldspathic, so that in the Lower Tradewater the sands have properties intermediate to those of the orthoquartzites below and the subgraywackes above.

The section above the New Burnside coals is characterized by a much greater proportion of sediments of known marine origin (limestones and shales), by thin lithologic units traceable over wide areas (often several states), by the notable dominance of shale compared to sandstone, by cyclical sedimentation, and by better developed coal beds. Both in outcrop and subsurface many of the associated sandstones fill prominent erosional channels. Changes in relative base level were the immediate cause of these channels as well as the probable cause of cyclical sedimentation.

The sandstones of this facies average some 16 percent (subsurface only) detrital matrix. Because the subgraywacke sandstones are basin wide, local depositional factors, such as proximity to a large delta, do not appear to be a satisfactory explanation for the proportion of clay matrix. Because of both basin-wide extent and association with change in kind as well as proportion of lithologies, the upward increase in clay matrix of the sandstones appears to have a direct tectonic explanation — an accelerating subsidence of the basin of deposition. A more negative basin is the probable cause of the wider lateral continuity of many of the lithologic units and the greater proportion of marine sediments. The sedimentary structures of these subgraywacke sandstones, however, differ little if at all from those of the sandstones below the New Burnside coals. Graded bedding and flow marks are very rare. Hence, even though the subgraywacke proportion of detrital matrix reflects poorer sorting at the site of deposition, these sandstones were deposited in shallow water. As in the underlying sandstones, the dominance of the nondirectional over directional load casts indicates that the regional depositional slope was small. That there was, however, a definitely preferred direction of sediment transport is shown by cross-bedding direction. Throughout the 1800 feet of Pennsylvanian sediments of this area, the modal transport direction was to the southwest.

A coupled low-lying coastal plain and marginal shallow shelf appears to provide the best large-scale model of the environment of deposition. Siever (1953, p. 215) suggested the existence of a somewhat similar physiographic couple during upper Chester sedimentation. On such a physiographic couple, oscillations of strand line would be far reaching, near-shore marine, littoral, tidal flat, and nonmarine sediments all could occur, opportunities for coal bed formation would be plentiful, and the development of erosional channels preceding sandstone deposition would be commonplace. This physiographic couple appears to have persisted throughout the entire period of Pennsylvanian deposition.

The lithologic contrasts above and below the New Burnside coals are the probable result of differential rates of subsidence upon such a physiographic couple. For example, available evidence (as quoted in Potter and Siever, 1956, part I) indicates that the sediments of the Caseyville group are a transgressive facies (sediment transport from northeast to southwest) in which by-passing played a significant role. The uniformity of the Caseyville-Mansfield flow pattern of the Eastern Interior coal basin (fig. 17) indicates that the sediments of this prograding physiographic couple had uniform depositional strike over wide areas. An initial slow rate of subsidence produced the well sorted sands of the Caseyville group. As time passed, the transport direction in the Williamson County area continued to be from northeast to southwest, but the Eastern Interior coal basin became more negative (subgraywacke sandstones) so that more sediments were entrapped and shale, marine sediments, and coal swamps became more significant. The decreasing competence of the sediment transport across this more negative physiographic couple is doubtless the reason for the dominance of shale over sandstone above the New Burnside coals. Sediment transport across a low lying coastal-plain—marginal-shelf that subsided at an accelerating rate with consequent change in lithologic proportions and sandstone type thus appears to have been the major feature of the environment of deposition.

If this interpretation is right, the sedimentary structures of the clastics should be similar to those of modern coastal-plain—shallow-shelf environments. Certainly cross-bedding, washouts with abundant locally derived conglomerates, ripple marks, and abundant drifted plant remains (in humid climates) are characteristic of modern coastal-plain—shallow-shelf clastics and are essentially identical to those of the Pennsylvanian clastics. The similarity extends to some of the small-scale, minor, internal sedimentary structures. Plates 7 and 8 permit a comparison of the fine sand-silt-shale interlaminations of Pennsylvanian sediments with those of the modern tidal flats of the Wadden Sea in the Netherlands, and with those of the near-shore clastics of the Texas Gulf Coast. The similarity points to an identity of small-scale processes of clastic deposition between this ancient coal basin and the modern Wadden Sea and Gulf Coast sediments.

Assuming the coastal-plain—marginal-shelf interpretation is correct, we might also expect to find some evidence of beach deposits, strand-line dunes, and offshore bars such as those found along the Texas Gulf Coast. In none of the sandstones has aeolian cross-bedding been observed. Dessication marks are very rare. This evidence, combined with an abundance of drifted plant remains and coal swamps implies a climate with abundant vegetation closely rimming the strand line. Littoral conditions probably were comparable to those of many of the modern coastal mangrove swamps of tropical regions.

Although their occasional marine fossils and close association with marine sediments indicate that significant proportions of the sandstones above the New Burnside coals may be of marine origin, neither subsurface (lithologic patterns) nor outcrop (textures and structures) evidence suggests that beach deposits or offshore bars were prominent. The poor sorting and roundness of the sandstones contrast sharply with those of many modern beach deposits. Although the Caseyville sands are well sorted, the structures of the Caseyville sandstone are clearly not those of modern beaches. The apparent absence of prominent beach deposits and offshore bars thus suggests that strand-line abrasion and transport were not extensive. This conclusion implies that the typical Pennsylvanian marine submergence of this low-lying coastal-plain—shallow-marine-shelf was not accompanied by strong shoreline current processes.

What contributions to environmental knowledge can be made by the clay minerals in these sediments? Murray (1953) investigated the clay mineralogy of some of the Tradewater, Carbondale, and McLeansboro sediments of the Eastern Interior coal basin and concluded that the presumed marine vs. nonmarine (Weller, 1931) portions of the cyclothem had contrasting clay mineral compositions.

Recognizing that the clay mineral composition of Pennsylvanian sandstones in both core and outcrop has been appreciably altered by post-depositional diagenesis, and that even shale can differ in composition from outcrop to subsurface, we investigated the clay mineralogy of the Trivoli cyclothem (all core samples) in detail. Figure 19 shows its variation in clay mineralogy. Segregation of the sandstone samples markedly decreases kaolinite abundance below the coal bed. The average clay mineral abundance (underclays excluded) above and below the Trivoli coal is shown in table 13 (A). Although mixed-lattice and chloritic materials are closely comparable for the two groups, there is variation in kaolinite and mica. In comparison to the clay mineral contrasts induced by post-depositional diagenesis in the sandstones, however, the kaolinite-mica variation is minor. However, Murray (1953, p. 59) also found more kaolinite and chlorite and less mica below rather than above the coal (table 13 (B)). More recently, Glass (1958) has also observed different clay mineral compositions in the shales above and below coal beds. Thus when inheritance and permeability effects are segregated, there appear to be some consistent differences

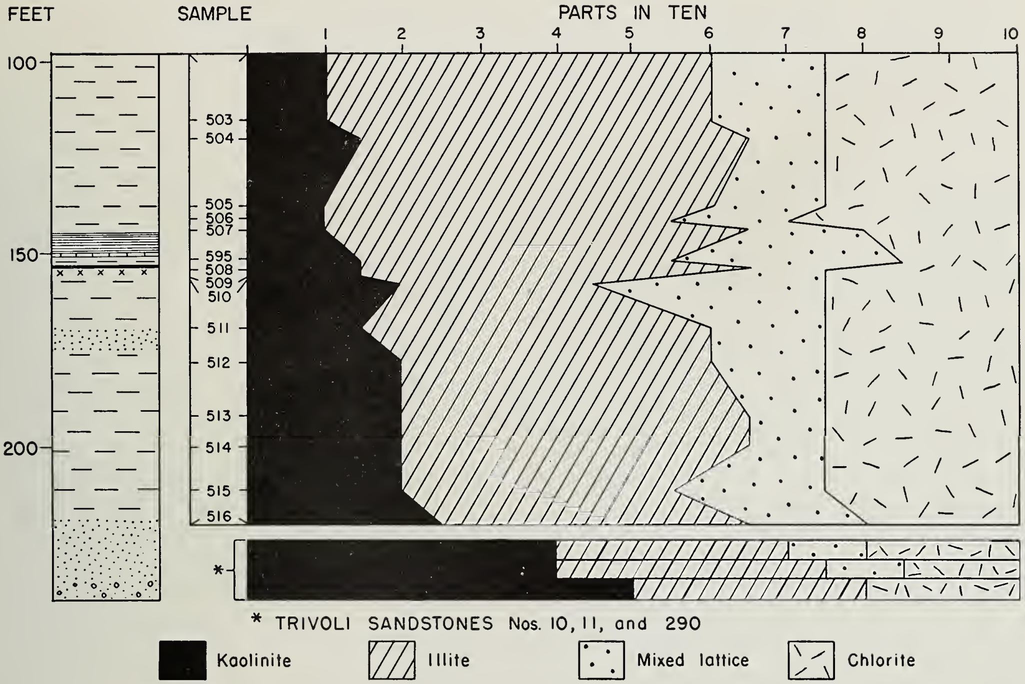

FIG. 19. — Clay mineral composition (subsurface samples only) of Trivoli cyclothem. Sample numbers identified in Appendix.

in clay composition above and below the coal beds of Pennsylvanian cyclothems.

Factors other than the possible difference between marine and nonmarine sedimentation, however, could be responsible for these contrasts. For example, even though we have eliminated the more permeable sandstones from the comparison, the shales below coals tend to be more silty and sandy than those above. The possibility that contrasts in clay-mineral permeability extend even to silty and sandy shales should be recognized. The effect of the acid environment of coal swamps on the underlying sediments (especially underclays) is another possible reason for contrasts in clay mineral composition above and below coal beds.

Another way to evaluate the environment of deposition is to contrast the clay mineral composition of the limestones with that of their associated subgraywacke shales. This would evaluate the effect of deposition and/or post-depositional diagenesis on clay mineral composition in a more alkaline environment. The limestones as a group can be quite variable in mixed-lattice and kaolinite content (as shown by table 8 (C)). These data show that some of the limestones are similar in clay mineralogy to the typical subgraywacke shales and that others differ markedly. This suggests that future studies of limestones might be rewarding for evaluating the role of clay-mineral diagenesis in alkaline environments.

Although the underclays may be a notable exception, the above interpretations emphasize the difficulties of interpreting the relationship between depositional environment and clay minerals. That there is some difference in subsurface clay-mineral composition between the subgraywacke and orthoquartzite shale facies, however, is shown in table 13 (C). Although mica is the dominant clay mineral of both, the subgraywacke shales average 2.4 and the orthoquartzite

Table 13.—Environmental Aspects of Clay Mineralogy

	Kaolinite	Mica	Mixed lattice	Chlorite	No. of samples
A. Trivoli cyclothem					
Above coal	1.1	5.1	1.4	2.4	5
Below coal	2.0	4.0	1.6	2.4	7
B. Composite contrast in subgraywacke facies (Murray, 1953)					
Above coal	1.4	7.4	—*	1.2	8
Below coal	2.1	6.3	—*	1.6	5
C. Orthoquartzitic versus subgraywacke facies shales					
Orthoquartzitic facies	1.1	6.1	1.4	1.4	17
Subgraywacke facies	1.5	4.6	1.5	2.4	38

* Included with mica.

shales 1.4 parts chlorite. Conversely, mica is more abundant in the orthoquartzitic shales than in those of the subgraywacke. Because of the subgraywackes' greater proportion of marine sediments, this contrast could be due to environmental differences. However, even though chlorite is somewhat more abundant in the subgraywackes, mica is less so and thus not all the differences are in the direction of the formation of illite by marine diagenesis. Inheritance differences between the shales of orthoquartzitic and the subgraywacke facies could be capable of accounting for these contrasts.

Obviously, the environmental interpretation of clay mineral composition in these sediments is not an easy task. What conclusions can be drawn from the difficulty of deducing the environment of deposition from the clay mineralogy of these sediments?

The close integration of clay mineral study with stratigraphy and sedimentary petrology maximized the likelihood of separating the effects of post-depositional diagenesis, depositional environment, and source-area contribution (inheritance) on clay mineral composition. This integration was very successful in evaluating the effect of post-depositional diagenesis on both shales and sandstones. It was not very successful, however, in separating the effects of inheritance from those of depositional environment. Others (Millot, 1953, p. 84; Grim and Bradley, 1955, p. 473) have suggested that the length of time the clay mineral remains at the depositional environment is an important factor. Probably because of rapid sedimentation, deposition in the near-shore marine, littoral, and nonmarine environments had minor effect on clay mineral composition. Although not conclusive, the available evidence suggests that in these sediments clay mineral composition is more dependent on source-area contribution than on depositional environment (with underclays as a notable exception). A presumed rapid rate of sedimentation is believed to be responsible for the greater source-area role. With slower sedimentation rates, the role of depositional environment might be more significant.

Thus one of the major conclusions of this study is to establish more firmly the view that because clay minerals are subject to quasireversible processes, they are a hybrid of stable source-area detritals on one hand and true chemical precipitates on the other. The evidence presented by this report thus suggests that in ancient sedimentation systems clay minerals are both allogenic and authigenic. They are predominantly allogenic where inheritance is dominant over either depositional environment or post-depositional diagenesis. Conversely, clay minerals are predominantly authigenic where depositional environment and/or post-depositional diagenesis are dominant.

TECTONICS AND CLIMATE

Provenance reconstruction indicates that as Pennsylvanian sedimentation in the Eastern Interior coal basin proceeded, progressively more and more crystalline rocks of either igneous or metamorphic origin contributed detritus. Progressive uplift and erosion of a crystalline core is inferred. That such progressive uplift of the source area was coupled with more rapid subsidence in the area of deposition is demonstrated by the correlation (in the transition and subgraywacke sandstones) between increasing clay matrix and more immature detrital (feldspar, chlorite, biotite, garnet, apatite, and poorly rounded tourmaline) components. Thus, throughout much of the eastern United States and Canada, Middle and Late Pennsylvanian time was marked by progressive differentiation between negative basins and positive source areas.

This tectonic differentiation was no doubt accompanied by progressive increase in orographic relief. Increase in continental orographic relief has been considered an essential factor in the progressive late Tertiary cooling that led to Pleistocene glaciation (Flint, 1947, p. 514-516; Emiliani, 1954). It seems probable that an increase in Middle and Late Pennsylvanian orographic relief would have induced a similar climatic change. Extending this viewpoint, the subgraywacke sandstones above the New Burnside coals may have been the early forerunners of progressively more intense Pennsylvanian tectonic and orographic contrasts that culminated in world-wide Permian climatic contrasts comparable to those of the present day.

SUMMARY

In the Eastern Interior coal basin a long period of erosion followed the termination of Mississippian sedimentation, producing widespread regional truncation. Rejuvenation at the close of the interval caused entrenchment of a dominantly southwestward-oriented system of stream channels that flowed toward the area of greatest subsidence. Companion rejuvenation of the source area made available mineralogically mature sediments that contained abundant quartz conglomerates. Approximately one-third of these source sediments had had long histories of abrasion. Sediment transport was dominantly from the northeast to the southwest, with progressive up-dip deposition. The Caseyville facies was deposited on a low lying coastal-plain—marginal-shelf. Well sorted, shallow-water orthoquartzitic sandstones accumulated on this physiographic couple. Although both marine and nonmarine sediments occurred, the dominance of sandstones (greater transport competence on a steeper regional slope?) minimized the likelihood of fossiliferous marine sediments.

In southern Illinois the Grindstaff sandstone marks the beginning of a greater rate of subsidence of the physiographic couple as well as the appearance of some feldspathic rocks in the source area. The source of the well rounded quartz pebbles was almost completely eliminated by this time. As feldspar, biotite, and chlorite increased gradually the proportion of well rounded source sediments decreased sharply. Although the site of deposition was becoming more negative throughout the Grindstaff—New Burnside coal interval, both lithologic proportions and general lateral persistence of major lithologies remained broadly similar to those of the Caseyville sediments. Clastic sedimentation of mixed marine and nonmarine origin was dominant. The first significant lithologic expression of the accelerating subsidence of the physiographic couple is found above the New Burnside coals.

Above the New Burnside coals this greater negative character resulted in a much greater proportion of rocks of known marine origin, well developed cyclical sedimentation, a much smaller proportion of sandstone (a lower regional slope?), and a greater lateral continuity in nearly all the lithologic units.

By this time source-area erosion had exposed significant metamorphic and/or igneous rocks, so that feldspar, biotite, chlorite, garnet, and apatite, and possibly other heavy minerals, were in transport to and across the physiographic couple. By now the proportion of source rocks with long histories of transportation had become negligible. Cross-bedding direction shows that in southern Illinois the regional slope of the coal basin persisted to the southwest from as early as the rejuvenation and entrenchment of the stream channels of the Mississippian-Pennsylvanian unconformity through the Upper Pennsylvanian at least to the time of deposition of the Mt. Carmel sandstone.

Thus the Pennsylvanian sediments along this southern portion of the Eastern Interior coal basin accumulated on a southwestward-dipping, low lying coastal-plain—shallow-marginal-shelf that became progressively more negative and probably more gently dipping with passage of time. This physiographic couple received more immature detritus as source-area erosion progressively unroofed metamorphic and/or igneous rocks and earlier sediment sources were overlapped. Increased tectonic differentiation between negative basins and positive source areas doubtlessly heightened orographic contrasts over significant portions of the continent and may have induced climatic changes in the Upper Pennsylvanian.

The above interpretations confirm the importance of petrology and sedimentary structures in obtaining source-area information, and also point out the limitations of both sand- or clay-fraction mineralogy in making environmental inferences. The present study reaffirms the importance of local and regional patterns of lithologic variation, fossil content, and sedimentary structures for obtaining knowledge of the environment of deposition.

What does the above summary contribute to our secondary objective — the examination of the interrelationships between gross lithologic variation, sedimentary structures, petrology, and clay mineralogy in an intracratonic coal basin?

The data of this study emphasize the interdependence of both lithologic types and proportions to sandstone petrology. A greater proportion of shale and marine sediments is associated with the subgraywacke sandstones. An accelerating rate of basin subsidence provides a common explanation. In contrast, this inferred accelerating subsidence was accompanied by only a comparatively minor change in clay mineralogy and no significant change in mechanism of sand transport.

APPENDIX

LOCATION OF SAMPLES

A. Shales

Sample number	*Location*	*Depth*	
		ft.	*in.*
500	Madison Coal Company Hole No. 25 NE¼ NE¼ NW¼ sec. 12, T. 8 S., R. 3 E., Williamson County, Illinois	54	6
501	Shale in sandstone (300) from Old Ben Hole No. 51, SW¼ SE¼ SW¼ sec. 29, T. 7 S., R. 4 E., Franklin County, Illinois		
502	Madison Coal Company Hole No. 25	84	
503	Madison Coal Company Hole No. 25	114	
504	Madison Coal Company Hole No. 25	120	
505	Madison Coal Company Hole No. 25	138	3
506	Madison Coal Company Hole No. 25	141	
507	Madison Coal Company Hole No. 25	143	9
508	Madison Coal Company Hole No. 25	153	2
509	Madison Coal Company Hole No. 25	153	6
510	Madison Coal Company Hole No. 25	154	
511	Madison Coal Company Hole No. 25	168	10
512	Madison Coal Company Hole No. 25	178	
513	Madison Coal Company Hole No. 25	190	9
514	Madison Coal Company Hole No. 25	199	2
515	Madison Coal Company Hole No. 25	211	
516	Madison Coal Company Hole No. 25	219	6
517	Madison Coal Company Hole No. 25	235	2
518	Madison Coal Company Hole No. 25	239	
519	Madison Coal Company Hole No. 25	243	6
520	Madison Coal Company Hole No. 25	262	
521	Madison Coal Company Hole No. 25	275	6
522	Madison Coal Company Hole No. 25	287	
523	Madison Coal Company Hole No. 25	297	
524	Madison Coal Company Hole No. 25	306	
525	Shale from sandstone exposed in road cut in NE¼ NE¼ NE¼ sec. 4, T. 9 S., R. 5 E., Saline County, Illinois		
526	Madison Coal Company Hole No. 25	352	7
527	Madison Coal Company Hole No. 25	357	
528	Madison Coal Company Hole No. 25	366	
529	Madison Coal Company Hole No. 25	371	
530	Madison Coal Company Hole No. 25	373	
531	Madison Coal Company Hole No. 25	436	
532	Madison Coal Company Hole No. 25	521	9
534	Madison Coal Company Hole No. 25	558	
535	Madison Coal Company Hole No. 25	576	
536	Madison Coal Company Hole No. 25	593	2
537	Madison Coal Company Hole No. 25	602	
539	Madison Coal Company Hole No. 25	637	
540	Madison Coal Company Hole No. 25	651	10
541	Madison Coal Company Hole No. 25	652	6
542	Madison Coal Company Hole No. 25	662	
543	Madison Coal Company Hole No. 25	663	
545	Madison Coal Company Hole No. 25	703	
546	Madison Coal Company Hole No. 25	722	
547	Madison Coal Company Hole No. 25	738	
548	Clay lens in Palzo sandstone exposed in strip mine in SW¼ NE¼ NE¼ sec. 20, T. 10 S., R. 5 E., Saline County, Illinois		
549	Clay lens in Davis sandstone exposed in New York Central Railroad cut in NE¼ NW¼ NE¼ sec. 30, T. 10 S., R. 5 E., Saline County, Illinois		
550	Gray shale 6 inches above Stonefort limestone in New York Central Railroad cut in NE¼ NW¼ NE¼ sec. 30, T. 10 S., R. 5 E., Saline County, Illinois		
551	Shale 1½ feet above Stonefort coal in New York Central Railroad cut in NE¼ NW¼ NE¼ sec. 30, T. 10 S., R. 5 E., Saline County, Illinois		
552	Shale below 2-foot sandstone (lowest exposed shale in New York Central Railroad cut in NE¼ NW¼ NE¼ sec. 30, T. 10 S., R. 5 E., Saline County, Illinois		
553	Madison Coal Company Hole No. 25	953	5
554	Madison Coal Company Hole No. 25	996	

Sample number	*Location*	*Depth*	
		ft.	*in.*
555	Madison Coal Company Hole No. 25	1039	6
556	Madison Coal Company Hole No. 25	1089	5
557	Madison Coal Company Hole No. 25	1167	5
558	Madison Coal Company Hole No. 25	1220	7
559	Madison Coal Company Hole No. 25	1226	3
560	Madison Coal Company Hole No. 25	1233	
561	Madison Coal Company Hole No. 25	1253	
562	Madison Coal Company Hole No. 25	1298	8
563	Madison Coal Company Hole No. 25	1321	8
564	Madison Coal Company Hole No. 25	1455	
565	Madison Coal Company Hole No. 25	1480	
566	Madison Coal Company Hole No. 25	1557	2
567	Madison Coal Company Hole No. 25	1562	
568	Madison Coal Company Hole No. 25	1572	
569	Madison Coal Company Hole No. 25	1581	
570	Madison Coal Company Hole No. 25	1587	
571	Madison Coal Company Hole No. 25	1593	
572	Madison Coal Company Hole No. 25	1600	
573	Madison Coal Company Hole No. 25	1604	2
574	Madison Coal Company Hole No. 25	1664	
575	Madison Coal Company Hole No. 25	1667	
576	Madison Coal Company Hole No. 25	1669	
577	Madison Coal Company Hole No. 25	1673	
578	Madison Coal Company Hole No. 25	1420	
579	Madison Coal Company Hole No. 25	1438	
580	Madison Coal Company Hole No. 25	1462	
581	Madison Coal Company Hole No. 25	1490	
582	Old Ben Coal Hole No. 24, SE¼ SE¼ NE¼ sec. 8, T. 5 S., R. 2 E., Franklin County, Illinois	176	
583	Old Ben Coal Hole No. 24, SE¼ SE¼ NE¼ sec. 8, T. 5 S., R. 2 E., Franklin County, Illinois	227	7
584	Old Ben Coal Company Hole No. 31, SW¼ SE¼ sec. 35, T. 5 S., R. 2 E., Franklin County, Illinois	208 to 192	
585	Shale under Shoal Creek limestone in NE¼ NE¼ SW¼ sec. 33, T. 7 S., R. 6 E., Saline County, Illinois		
586	Shale below DeKoven coal and above DeKoven sandstone from strip mine in SW¼ NE¼ NE¼ sec. 20, T. 10 S., R. 5 E., Saline County, Illinois		
587	Shale above Davis Coal and below DeKoven sandstone at SW¼ NE¼ NE¼ sec. 20, T. 10 S., R. 5 E., Saline County, Illinois		
588	Approximately 5 feet above Curlew coal from abandoned quarry in SE¼ SE¼ SE¼ sec. 25, T. 10 S., R. 3 E., Williamson County, Illinois		
589	Clay lens in Shoal Creek sandstone in NW¼ NW¼ SW¼ sec. 3, T. 7 S., R. 5 E., Saline County, Illinois		
590	Shale over coal exposed on east side of Illinois Central Railroad cut in NW¼ SE¼ SE¼ sec. 2, T. 11 S., R. 5 E., Pope County, Illinois		
591	Underclay of coal exposed on east side of Illinois Central Railroad cut in NW¼ SE¼ SE¼ sec. 2, T. 11 S., R. 5 E., Pope County, Illinois		
592	Shale over New Burnside coal and below Creal Springs sandstone in NW¼ NE¼ SW¼ sec. 4, T. 11 S., R. 4 E., Johnson County, Illinois		
593	Shale below Curlew coal exposed in abandoned quarry at SE¼ SE¼ SE¼ sec. 25, T. 10 S., R. 3 E., Williamson County, Illinois		
594	Shale 2 feet above Curlew limestone from abandoned quarry in SE¼ SE¼ SE¼ sec. 25, T. 10 S., R. 3 E., Williamson County, Illinois		
595	Silty shale below Stonefort coal and above 2-foot sandstone in New York Central Railroad cut in NE¼ NW¼ NE¼ sec. 30, T. 10 S., R. 4 E., Saline County, Illinois		
596	Madison Coal Company No. 25	1620	
597	Drury shale from road cut in NE¼ NE¼ NW¼ sec. 34, T. 11 S., R. 2 E., Johnson County, Illinois		
598	Shale exposed in drainage diversion ditch on west side of Illinois Central Railroad cut in NW¼ SW¼ NE¼ sec. 31, T. 11 S., R. 5 E., Pope County, Illinois		
599	Shale as in 598		
600	Shale from road cut on Illinois highway 145 in SW¼ SW¼ sec. 14, T. 12 S., R. 5 E., Pope County, Illinois		
601	Shale as in 600		
602	Shale as in 600		

B. Sandstones

Sample number	*Location*	*Depth*
10	Trivoli sandstone from Madison Coal Company Hole No. 25	169′ 6″ to 170′
11	Trivoli sandstone from Madison Coal Company Hole No. 25	218′ to 218′ 5″
12	Trivoli sandstone from Madison Coal Company Hole No. 25	239′ to 239′ 10″
13	Anvil Rock sandstone from Madison Coal Company Hole No. 25	405′ 8″ to 406′
14	Pleasantview sandstone Madison Coal Company Hole No. 25	620′ to 620′ 6″
16	Davis sandstone Madison Coal Company Hole No. 25	801′ 8″ to 802′ 4″
17	Tradewater sandstone from Madison Coal Company Hole No. 25	902′ 7″ to 903′
18	Tradewater sandstone from Madison Coal Company Hole No. 25	950′ to 950′ 9″
20	Tradewater sandstone from Madison Coal Company Hole No. 25	1065′ to 1065′ 6″
21	Tradewater sandstone from Madison Coal Company Hole No. 25	118′ 8″ to 119′ 2″
22	Tradewater sandstone from Madison Coal Company Hole No. 25	
23	Tradewater sandstone from Madison Coal Company Hole No. 25	1369′ to 1369′ 6″
24	Tradewater sandstone from Madison Coal Company Hole No. 25	1393′ 6″ to 1394′
25	Tradewater sandstone from Madison Coal Company Hole No. 25	1426′ 3″ to 1426′ 8″
26	Caseyville sandstone from Madison Coal Company Hole No. 25	1517′ 11″ to 1518′ 9″
27	Caseyville sandstone from Madison Coal Company Hole No. 25	1608′ to 1608′ 10″
28	Caseyville sandstone from Madison Coal Company Hole No. 25	1653′ 10″ to 1654′ 6″
40	Caseyville sandstone from Madison Coal Company Hole No. 25	1484′ 6″ to 1485′
41	Caseyville sandstone from Madison Coal Company Hole No. 25	1541′ 4″ to 1542′
42	Caseyville sandstone from Madison Coal Company Hole No. 25	1556′ to 1556′ 6″
290	Trivoli sandstone from Madison Coal Company Hole No. 25	179′ 8″ to 180′
291	Sandstone 10 feet above coal No. 5a in Delta strip mine in SE¼ SW¼ SE¼ sec. 28, T. 9 S., R. 4 E., Williamson County, Illinois	
292	Palzo sandstone in SW¼ NE¼ NE¼ sec. 20, T. 10 S., R. 5 E., Saline County, Illinois	
293	DeKoven sandstone from Will Scarlet mine of Stonefort Coal Company in sec. 14, T. 10 S., R. 4 E., Williamson County, Illinois	
294	Two-foot sandstone approximately 15 feet below Stonefort limestone in New York Central Railroad cut in NE¼ NW¼ NE¼ sec. 30, T. 10 S., R. 5 E., Saline County, Illinois	
299	Tradewater sandstone from Madison Coal Company Hole No. 25	901′
300	Old Ben Coal Company Hole No. 51, SW¼ SE¼ SE¼ sec. 29, T. 9 S., R. 4 E., Franklin County, Illinois	197′ 8″ to 198′
301	Shoal Creek (?) sandstone in SW¼ SW¼ SE¼ sec. 1, T. 8 S., R. 5 E., Saline County, Illinois	
303	Creal Springs sandstone from abandoned quarry in SE¼ SE¼ SE¼ sec. 25, T. 10 S., R. 3 E., Williamson County, Illinois	
328	Sandstone from road cut in NW¼ NE¼ NE¼ sec. 4, T. 9 S., R. 5 E., Saline County, Illinois	
330	Mt. Carmel sandstone in road cut in SW¼ NE¼ SE¼ sec. 25, T. 7 S., R. 3 E., Franklin County, Illinois	

C. Limestones

Sample number	*Location*	*Depth*
298	Old Ben Coal Company Hole No. 51, SW¼ SE¼ SE¼ sec. 29, T. 7 S., R. 4 E., Franklin County, Illinois	93′ to 100′
312	Curlew limestone from Creal Springs quarry in SE¼ SE¼ SE¼ sec. 25, T. 10 S., R. 3 E., Williamson County, Illinois	
314	Madison Coal Company Hole No. 25	281′ to 283′ 10″
315	Bankston Fork limestone from Madison Coal Company Hole No. 25	388′
316	Trivoli limestone from Madison Coal Company Hole No. 25	148′ 10″ to 149′ 3″
318	Cutler limestone from Madison Coal Company Hole No. 25	362′ 1″
381	Herrin limestone from Madison Coal Company Hole No. 25	447′
604	St. David limestone Madison Coal Company Hole No. 25	535′ 10″
605	Stonefort limestone from Wise Ridge NE¼ NE¼ SE¼ sec. 4, T. 11 S., R. 4 E., Johnson County, Illinois	

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